Real-time Monitoring of Ventilation Rate for Measuring Tomato Plants Photosynthetic Rate using CO2 Balance Method in a Naturally Ventilated Greenhouse

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（自然換気温室における CO_2 収支法を用いたトマト植物群落の光合成速度算定のための換気率のリアルタイム測定）

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SUMMARY

In real-time monitoring of photosynthesis in a naturally ventilated greenhouse, estimating the necessary ventilation rate is a prerequisite for determining the photosynthetic rate via CO_2 balance method. There are various methods for measuring the ventilation rate method, i.e., tracer gas, heat balance, and water vapor balance. However, each method has a special challenge in practice. It is necessary to clarify the difference between the accuracy and operability of ventilation rate methods.

The tracer gas (TG) is the most widely used ventilation rate measurement method in conjunction with either the constant flow or the tracer gas method. Many authors showed that the tracer gas showed excellent performance of ventilation rate prediction at leakage and low ventilation conditions under a different type of greenhouse. However, the TG method experiences numerous disadvantages in large-scale greenhouses with a large ventilation opening area because a large amount of CO_2 gas must be supplied to maintain the CO_2 concentration in a greenhouse higher than that in outside air. On the contrary, the heat balance method (HB) have conducted to model greenhouse environments and estimate the rate of ventilation that mainly influenced by solar radiation quality in a greenhouse. There are several difficulties in choosing values of parameters; for instance: solar heat gain correction factor required more sensors to obtain average values of the respective environmental conditions, the shadow effect of direct radiation on a sensor, etc. Furthermore, the HB method has better prediction of ventilation rate under large ventilation opening area, but it has a problem to predict the ventilation rate at small window aperture. It should be clarified in advance about this problem.

In terms of water vapor balance method (WVB), this method uses water vapor from evapotranspiration process for measuring the ventilation rate. The method had a good agreement with other methods using tracer gas, i.e., CO_2 and N_2O in such a greenhouse cultivated with mature plants and in smaller ventilation opening area condition. However, most of the ventilation rate performance in the previous research conducted under small ventilation opening area. Furthermore, in context of transpiration measurement as a main source of water vapor for the WVB method, it is usually measured by the electronic weighing device. This method has reasonably good accuracy, but time interval factor for measuring transpiration should be considered. It is related to the accuracy of the device to measure transpiration rate. Continuous monitoring of photosynthesis should be employed in the short-term interval. Thus, it should be considered how to measure and monitor the transpiration in the greenhouse continuously. This condition, moreover, has to be known on a time scale suitable for monitoring of the ventilation rate and the photosynthetic rate.

Almost all techniques to measure the ventilation rates through a naturally ventilated greenhouse suffer from a lack of a standard and reliable reference technique to compare their accuracies. When using the TG method to determine the ventilation rates, large variations in gas concentration was observed inside the ventilated greenhouse due to non-perfect mixing. This problem can be minimized by using more sampling points to assess the ventilation rates in a naturally ventilated greenhouse. This method was useful as a reference method for research and calibration purposes. Therefore, the last two techniques were evaluated method as practical tools for use in field measurements of the ventilation rates thoroughly a naturally ventilated greenhouse that carried on the short-

time interval. Also, the methods were validated by the TG method as reference under several of window aperture in different seasons.

The main goal of this recent study was to evaluate the three-type measurement of ventilation rate method for continuous monitoring of tomato plants photosynthetic rate in a naturally ventilated greenhouse. Experiments were performed to achieve the main goal in a single-span type greenhouse through different seasons in Gifu, Japan. The ventilation rates were determined using the tracer gas technique (TG), the heat balance method (HB), and the water vapor balance method (WVB). Continuous measurements of temperature, humidity, solar radiation, and CO_2 concentration, transpiration, and wind speed were performed. Also, the calculated photosynthetic rate based on the above ventilation rate method was validated using a Li-COR 6400 portable photosynthesis device.

The results revealed the TG as reference showed extremely reliable for measuring ventilation rates for various ventilation opening areas. Results showed that the ventilation rates were higher when wind velocities were higher and without cultivation. However, when for a large ventilation opening area (like in late spring, summer, and early autumn seasons), a considerable amount of TG is required to maintain high and uniform concentration in a greenhouse. Furthermore, it is difficult to maintain a uniform CO_2 concentration in the greenhouse because the outdoor airflow affects the CO_2 concentration distribution in the greenhouse. Practically, it is quite challenging to implement the TG method for continuously monitoring the ventilation rate because of the above reasons and high cost. The results obtained from the HB and WVB methods can be used for monitoring the ventilation rate for moderate and large ventilation opening areas.

The ventilation rates measured using the HB and WVB methods showed similar variation trends with time, and the ventilation rate changed considerably with the wind speed outside the greenhouse. The HB method provided accurately predicted the ventilation rate not only for the maximum window aperture but also for the moderate window aperture (more than 10% of window aperture). In this study found that the HB method gave better results under large ventilation opening area with solar radiation condition should be more than 200 W m^{-2}. On the contrary, the HB resulted in a lower value than the reference when the radiation was below 200 W m^{-2} or when the vents were closed and smallest of window aperture conditions, like in late autumn, winter, and early spring seasons. This problem can be elucidated using an evaluation of the energy balance expressed as a percentage of the net radiation collected in the greenhouse. In this thesis, the heat balance energy graph was proposed to determine the minimum of window aperture (W), minimum of the energy should be removed from the greenhouse by ventilation, and a minimum of inside solar radiation that would give better result prediction of the ventilation rate using the heat balance method.

The WVB method showed reliable results through different seasons and acceptable results to several of the window aperture. The results showed the ability of the WVB method that can predict the ventilation rate not only under a small ventilation opening area but also until a high level of the window aperture. Therefore, the WVB method is suitable for the continuous measurement of the ventilation rate because it is simple and can be used for different window apertures. However, it should be noted that this method can perform well when the vapor pressure deficit in optimal condition for plants in a greenhouse. Also, the results recommended a high accuracy of electronic balance device (weighing method) and the sap flow measurements for measuring transpiration as the main source of water vapor in a greenhouse environment. The measured transpiration via the sap flow gave a better result than the flow meter and water level sensor due to the time lag of the devices used to measure transpiration.

概要

CO_2 収支法を用いて，自然換気温室で栽培する植物群落の光合成速度をリアルタイムで算定するには，温室換気率の連続測定が必要である．換気率の測定は，トレーサーガス，熱収支，水蒸気収支などさまざまな方法があるが，実際にはそれぞれの方法には長所と欠点があり，換気量法の精度と操作性の違いを明らかにする必要がある．

トレーサーガス（TG）法は，定流量法またはトレーサーガス法と組み合わせて最も広く使用されている換気率の測定方法である．多くの研究では，トレーサーガスが，異なるタイプの温室の下で，漏れおよび低換気条件での換気率予測の優れた性能があることが示されている．しかし，温室の CO_2 濃度を外気よりも高く維持するために，CO_2 ガスを大量に供給しなければならないため，開口面積の大きな大規模温室では，TG 法の長期使用は現実的ではない．

熱収支法（HB）は温室環境の熱収支式を利用し，主に温室の吸収日射量に影響される換気率の推定に用いられている．熱収支式の各パラメータの測定にはいくつかの課題がある．たとえば，吸収日射量の補正係数は，それぞれの環境条件の平均値，センサーへの直接放射の影の効果などを考慮するためにより多くのセンサーを必要とする．さらに，HB 法は，開口面積が大きい条件下における換気率の予測は信頼性が高いが，開口部が小さな温室の換気率予測には問題が多く，この問題を事前に明らかにしておく必要がある．

水収支（WVB）法は，蒸発散プロセスで生じる水蒸気を使用して換気率を測定する．この方法は，植物群落が発達し開口部の小さな温室において，トレー

サーガス（CO_2，N_2O など）法の結果とよく一致した．しかしながら，既存の研究の多くは，開口面積の小さな温室での測定に限定されている．さらに，WVB法の主な水蒸気源である蒸散量は，通常，電子計量装置によって測定されている．この方法は精度が高いが，蒸散の測定時間の間隔を考慮する必要がある．これは，蒸散率を測定するデバイスの精度が関連する．光合成速度の連続測定に水収支法で求めた換気率を使用する際には，測定間隔が短期間のデータを採用するべきである．したがって，温室の蒸散を継続的に測定およびモニタリングできる方法および，換気率と光合成率のモニタリングに適した時間スケールで明らかにする必要がある．

現在のところ，自然換気温室の換気率測定において，それらの精度を比較するための標準的で信頼性の高い評価法が確立されていない．TG法を使用した換気率の測定は，混合が不完全な場合，温室内のガス濃度に大きな濃度のばらつきが発生しやすい．この問題は，より多くのサンプリングポイントを使用して自然換気の温室の換気率を評価することで最小限に抑えられる．この方法は，研究および校正目的の参照方法として有効であった． TG 法は，自然換気温室の換気率を短時間で継続的に実施するには実用的なツールである．また，この方法を利用して，異なる季節における異なる開口面積の換気率の測定の基準として利用できた．

以上のような背景より，本研究の主な目的は，自然換気の温室におけるトマト植物の光合成速度の連続的なモニタリングに適した換気率測定法として 3 種類の測定法を評価することとした．岐阜大学に建設された単棟ガラス温室を使用して，各季節において換気率の測定試験を実施した．換気率の測定に，トレ

ーサーガス（TG）法，熱収支（HB）法，および水収支（WVB）法を使用した．それらの測定に必要なパラメータである温度，湿度，日射量，CO_2 濃度，蒸散量，風速を連続測定した．また，上記の換気率のデータを利用して算定した光合成速度は，LI-COR 6400 ポータブル光合成装置を使用して，その値が妥当か検証した．

その結果，TG法は換気率の基準値として有効であり，さまざまな開口条件下の換気率を測定する上で非常に信頼性が高いことが明らかとなった．その結果，風速がより強く無植栽の温室は，無風速で植栽のある温室よりも換気率が高いことを示した．ただし，換気口の面積が広い場合（晩春，夏，初秋など），温室の CO_2 濃度を均一に保つには，かなりの量の CO_2 ガスが必要であるだけでなく，温室の CO_2 濃度分布は外気の流れに影響されるため，温室内の CO_2 濃度を均一に保つことは困難であった．以上の点とガスのランニングコストの高さのため，換気率を継続的にモニタリングする方法として TG 法は不適であった．HB および WVB 法で得られた結果は，中程度および大きな換気開口領域の換気率のモニタリングに使用できた．

同一条件においてHBおよびWVB法により測定された換気率は，同様の経時変化を示し，換気率は温室外の風速の影響を受けた．HB 法による測定値は温室開口部が最大のときだけでなく，中程度の条件でも正確に換気率を測定できた．特に， HB 法は，温室内の吸収日射量が 200 W m^{-2} 以上でかつ開口面積が大きな条件の下でより良い結果が得られることが明らかとなった．反対に，HB 法は，吸収日射量が 200 W m^{-2} で，かつ換気口が閉鎖され気味となる晩秋，冬，春の初めのような季節では TG 法で求められた換気率よりも低い値となった．

この原因は，温室の熱収支から説明できる．すなわち，前述の条件では吸収日射量のうち，換気で排出される熱の割合が低下するため，熱収支法による換気率測定の精度が低下すると結論づけられた．この結果は，窓の開口部（W）の最小値，換気によって温室から除去する必要のあるエネルギーの最小値，および室内の日射量を最小限に抑えるための熱収支エネルギーグラフとして提示できた．

WVB法は，さまざまな季節を通して信頼できる結果を示し，さまざま開口条件下でも信頼できる値を求めることができ，小さな換気開口面積の下だけでなく，窓の開口部の高レベルまで換気量を予測できた．したがって，WVB法は測定システムがシンプル（内外の絶対湿度，蒸散速度の測定）であるが，さまざまな開口条件でも使用できるため，栽培が長期間となるトマト群落の光合成速度の算定に必要となる換気率の連続測定に適している．ただし，温室内の植物の蒸散量が少ない場合，この方法は精度が低下する可能性がある．また，本研究では WVB 法における温室環境での水蒸気の主な発生源としての蒸散量測定には，高精度の電子天秤装置（計量方法）と樹液流測定を推奨した．茎流を介して測定される蒸散速度は，流量計や水位センサーよりもタイムラグが少なく，精度の高い測定が可能であった．

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CHAPTER 1 General introduction

Some of the content in this chapter has been accepted for publishing as:
Tusi, A. and T. Shimazu (2020) The Essential factor of ventilation rate in prediction of photosynthetic rate using the CO_2 balance method. Reviews in Agricultural Sciences.

1.1. Need and challenges for monitoring of the greenhouse ventilation rate

An important process in a naturally ventilated greenhouse is ventilation rate or the air exchange rate between the inside greenhouse and the environment. It directly affects the exchanging process of heat, water vapor generated from evapotranspiration, and other gases to or from the inside greenhouse. The important roles of the ventilation system in a greenhouse are to control the temperature, to depress an excessive level of humidity, and also, to replenish the CO_2 concentration. Moreover, estimating the necessary ventilation rate is a prerequisite for determining the photosynthetic rate via CO_2 balance method in a naturally ventilated greenhouse. The accurate ventilation rate measurement improves the accuracy of the photosynthetic rate. Therefore, more insight into this performance in continuously monitoring is crucial to evaluate for computing the photosynthetic rate accurately.

Measuring the net canopy photosynthesis of crop had described in detail by Hand (1973a) under the daylight controlled-environment cabinet. Also, Hand (1973b) has reviewed the many different methods of gas exchange measurement in which the plant enclosures can be of open, closed, or mixed systems. Furthermore, Lake et al. (1968) had necessarily applied to an open system with null point compensation for CO_2, whereas maintained CO_2 concentration inside the greenhouse at almost the same level as CO_2 level in outside (or $\Delta CO_2 \approx 0$). Generally, the CO_2 gas exchange method was conducted to measure photosynthesis based on CO_2 concentration changes inside and outside the greenhouse. It is also well-known as the CO_2 balance method, as presented in Eq. 1.1 and Fig. 1.1. CO_2 greenhouse fluxes occur through ventilation, CO_2 supply, CO_2 from soil respiration, changes in the greenhouse CO_2 concentration, and net photosynthesis.

$$\frac{V}{wA}\frac{dC_{in}}{dt} = I + S + \frac{G}{w}(C_{out} - C_{in}) - P_n \tag{1.1}$$

Where V and A are, respectively, the volume (m^3) and the cultivable ground area (m^2) of the greenhouse; dC_{in}/dt is the time change of CO_2 concentration in the greenhouse (μmol mol^{-1} min^{-1}); w is the conversion factor of CO_2 from volume to molecular weight (0.0224 m^3 mol^{-1} at 20 °C, 101.325 kPa); I is the CO_2 injection flux or supply (μmol m^{-2} min^{-1}); S is the CO_2 output from soil respiration (μmol m^{-2} min^{-1}); G is the ventilation flux (m^3 m^{-2} min^{-1}), C_{in} is the CO_2 concentration inside the greenhouse (μmol mol^{-1}); C_{out} is the concentration of CO_2 outside the greenhouse (μmol mol^{-1}); and P_n represents net photosynthetic rate per floor area (μmol m^{-2} min^{-1}).

Several authors in their experiments considered that the difference between CO_2 concentration inside and outside the greenhouse was null, and the CO_2 respiration from soil was negligible due to covered by plastic (Hand, 1973a; Hand et al., 1992; Zekki et al., 1999). When the null balance concept applied (Hand, 1973a), the CO_2 concentration in the greenhouse was maintained at the same level with the ambient CO_2 concentration at the outside greenhouse (around 350 – 380 μmol mol^{-1}), and the value of CO_2 flux can be negligible. It was conducted to minimize the effect of exchanges via infiltration and exfiltration. Hence the net photosynthesis equation can thus be determined based on greenhouse CO_2 concentration and the injected CO_2 in the greenhouse system. However, this condition had applied under the ventilation condition was closed or leakage condition (Eq. 1.2).

$$P_n = I - \frac{V}{wA}\frac{dC_{in}}{dt} \tag{1.2}$$

Furthermore, the photosynthetic rate from the CO_2 balance method is validated by an infrared gas analyzer (IRGA). It was used to measure CO_2 concentration, whereas samples of greenhouse were drawn using nylon tube placed within the canopy, at mid-height (Hand, 1973; Nederhoff *et al.*, 1989; Hand et al., 1992; Ehler, 1991). Most researchers conducted the ventilation rate using the tracer gas technique (TG) to calculate the photosynthetic rate via the CO_2 balance method with an IRGA device on their experiments.

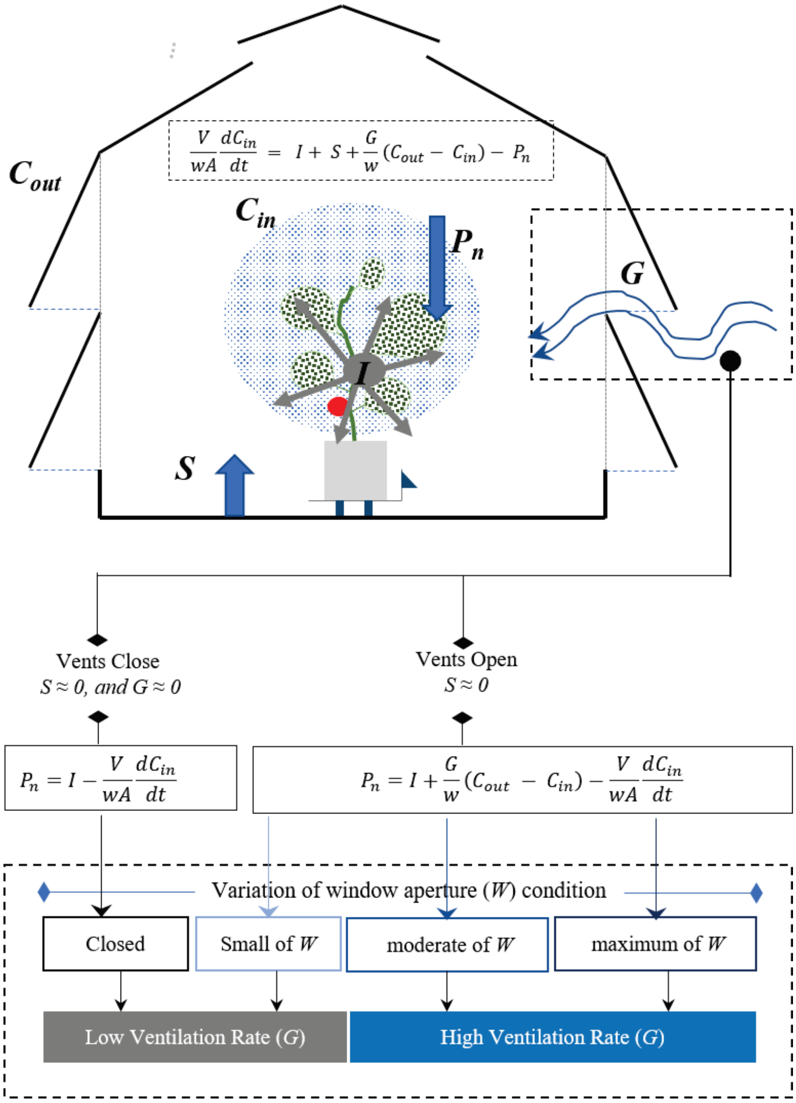

Fig. 1.1 Schematic diagram of the CO_2 balance method with CO_2 supply (I) in a greenhouse for estimating the photosynthetic rate (P_n). The changes of concentration between outside and inside (C_{out} - C_{in}) and the changes of inside concentration during the time of measurement (dC_{in}) in total volume (V) per floor area of greenhouse (A) that affected by window aperture (W) condition, as presented by ventilation rate value (G). Assuming the CO2 release from the soil was zero ($S \approx 0$) due to covered by plastic and using the hydroponic cultivation method (with soilless culture).

Table 1.1 Summary of reviewed literature suggesting photosynthesis rate measurement and simulation in the greenhouse system from 1989 to 2017

Year	Photosynthesis (measurement/model)	Measurement methods of ventilation rate	References
1989	Dynamic simulation model using the CO_2 balance method	Tracer gas using N_2O	Nederhoff et al. (1989)
1990	Measurement of photosynthesis using a CO_2 balance method every 30 minutes	Tracer gas using N_2O	Gijzen, Vegter, and Nederhoff (1990)
1991	An hourly net photosynthesis measurement using CO_2 balance method at a low ventilation rate	Tracer gas	Ehler (1991)
1994	Estimation of canopy photosynthesis based on CO_2 balance method	the using model developed by Fernandez and Bailey (1992); function of wind speed and the opening angle	Chalabi and Fernandez (1994)
1999	Measurement of net photosynthetic rate using the CO_2 balance method	Negligible (null CO_2 balance)	Zekki et al. (1999)
2017	Monitoring of a plant canopy using CO_2 balance technique	Energy balance method	Takakura et al. (2017)
1991	The black box model of the photosynthesis simulation model	-	Ehler (1991)
1994	Simulation of canopy photosynthesis based on mechanistic models (Acock model, and Challa and Schapendonk model)	-	Chalabi and Fernandez (1994)
1999	Simulation of photosynthesis using the TOMGRO model which integrates Acock's model	-	Zekki et al. (1999)
2011	Simulation of photosynthesis based on simple leaf photosynthesis after the careful consideration of leaf area index and light density distribution in the greenhouse and also considered the influence of the environment (temperature, CO_2 concentration, and moisture).	-	Zhang and Wang (2011)
2013	Model of monitoring photosynthesis based on CO_2 concentration and photosynthesis data measurements that analyzed using the back-propagation neural network model.	-	Wang et al. (2013)

Table 1.1 showed the photosynthetic rate in a greenhouse calculated based on a greenhouse climate system (Nederhoff et al., 1989; Gijzen et al., 1990; Chalabi and Fernandez, 1994; Zekki et al., 1999; Zhang and Wang, 2011; Wang et al., 2013) and plant monitoring (Dieleman et al., 2017). It was found that the CO_2 balance is a popular method and becomes the primary technique to calculate photosynthesis in a greenhouse. Many

authors have solved the ventilation rate value, as an unknown parameter in the CO_2 balance equation, using the tracer gas technique using N_2O (Nederhoff et al., 1989; Gijzen et al., 1990; Ehler, 1991). They have conducted the ventilation rate using N_2O tracer gas under leakage and small window aperture (low ventilation rate), as shown in Table 1.2 and Fig. 1.2. It is clear that the CO_2 balance using the null balance method is intended to work at meager ventilation rates (Zekki et al., 1999; Hand et al., 1992) at a long interval calculation of photosynthesis between 10 – 15 minutes.

Table 1.2 Summary of reviewed literature suggesting photosynthesis rate measurement using the CO_2 balance method

CO_2 concentration		Ventilation rate	Ventilator	Model Comparison	Authors
ppm	device				
350	IRGA	- (null balance method)	Closed all-day	TOMGRO model (a mechanistic model)	Zekki et al. (1999)
350	IRGA	- (null balance method)	Closed and small ventilator	a) Empirically based on a quadratic regression b) Mechanistic model as developed by Thornley et al. (1992)	Hand et al. (1992)
350 - 1000	IRGA	Model as developed by Fernandez and Bailey, 1992)	Small ventilator	Mechanistic model: Acock et al., (1978) and Challa and Schapendonk (1984)	Chalabi and Fernandez (1994)
350-1500	IRGA	Tracer gas (N_2O)	Small ventilation	The SUCROS model (Gijzen and Ten Cate, 1988)	Nederhoff et al. (1989)
350 - 1000	DGT infrared CO_2 scanner (IRGA)	Tracer gas (N_2O)	Low and high ventilation	The black box model of the photosynthesis simulation model	Ehler (1991)
400 - 1200	IRGA	Tracer gas (N_2O)	Low ventilation	-	Hand (1973)
No information	CO_2 engine K30	Energy balance method	Low ventilation	-	Takakura et al. (2017)

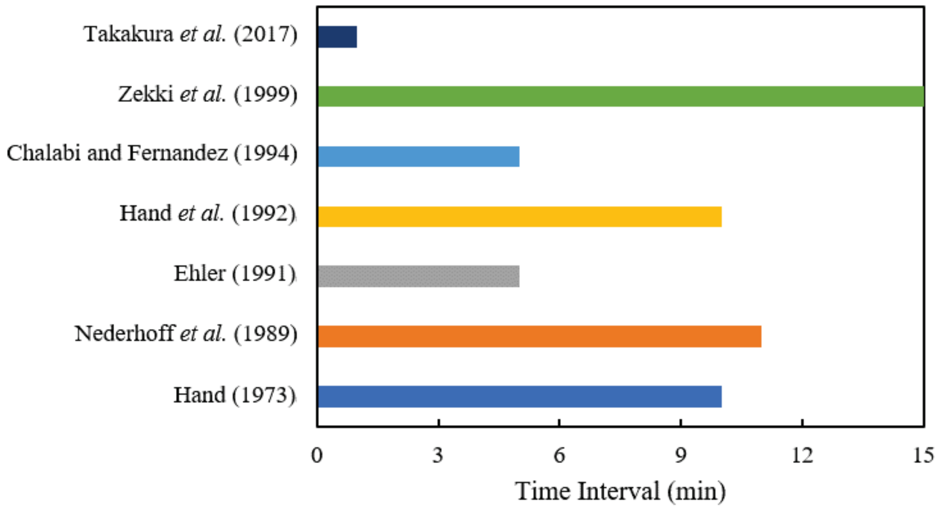

Fig. 1.2 The interval time of the photosynthetic rate measurement in different sources based on CO_2 balance method in a greenhouse

In contrary, the ventilation rate value should be added on the CO_2 balance calculation at moderate or high ventilation rate condition with interval calculation of photosynthesis between 5 – 11 minutes as mentioned by Chalabi and Fernandez (1994), Nederhoff et al. (1989), and Ehler (1991), as shown in Table 1.2 and Fig. 1.1. The ventilation rate value should be added on the CO_2 balance calculation at moderate or high ventilation rate condition as mentioned by Chalabi and Fernandez (1994), Nederhoff et al. (1989), and Ehler (1991). Furthermore, Takakura et al. (2017) calculated the canopy photosynthesis based on CO_2 balance and ventilation rate using the energy balance technique under a high ventilation rate condition (Table 1.1). However, they obtained data of the canopy photosynthesis were scattered due to frequent changes in the ventilation amount. Therefore, it is vital to add and evaluate the ventilation rate performance used in the CO_2 balance equations, especially during the late spring and summer season through a naturally ventilated greenhouse. This thesis was extensively elucidated comprehensively.

Furthermore, the calculated photosynthesis rate using CO_2 balance was not validated with the direct measurement method of photosynthesis yet, for instance: LI-6400XT, LI-6800 portable photosynthesis system from LI-COR Co., USA. There was a paper that confirmed the photosynthetic rate of single leaves based on the backpropagation neural network with photosynthesis measurement using Li-COR (Wang et al., 2013). Hence, it is essential to compare and verify the photosynthesis rate based on the CO_2 balance method and ventilation rate prediction with direct leaf photosynthesis measurement in a greenhouse. Also, there is a lack of information about the performance of photosynthesis prediction using the CO_2 balance method with ventilation rate method prediction other than the tracer gas technique, i.e., the heat balance method and the water vapor balance method. Therefore, further research about these needs to be conducted and performed under different window aperture, from low until high ventilation rate.

In terms of the heat balance method (HB), the technique has conducted to model greenhouse environments and estimate the rate of ventilation. Generally, the heat balance method was developed using current microclimate data obtained from the meteorological station around the greenhouse. Some researchers have developed heat balance models. Fig 1.3 showed that the correlation value of the air exchange rate using the heat balance method and the reference (the tracer gas method using N_2O) increased linearly with enlargement of the roof vents in the large-scale greenhouse. Fernandez and Bailey (1992) noted that measurement precision increased with the length of the measurement time scale and vent opening. For higher ventilation conditions, it was found that the energy balance gives better results for higher ventilator apertures (Fernandez and Bailey, 1992; Baptista et al., 2001). However, the R-squared values found weak of correlation value at below

10% of W (Fig. 1.3). Also, it was found at a small-scale greenhouse, as mentioned by Yasutake et al. (2017).

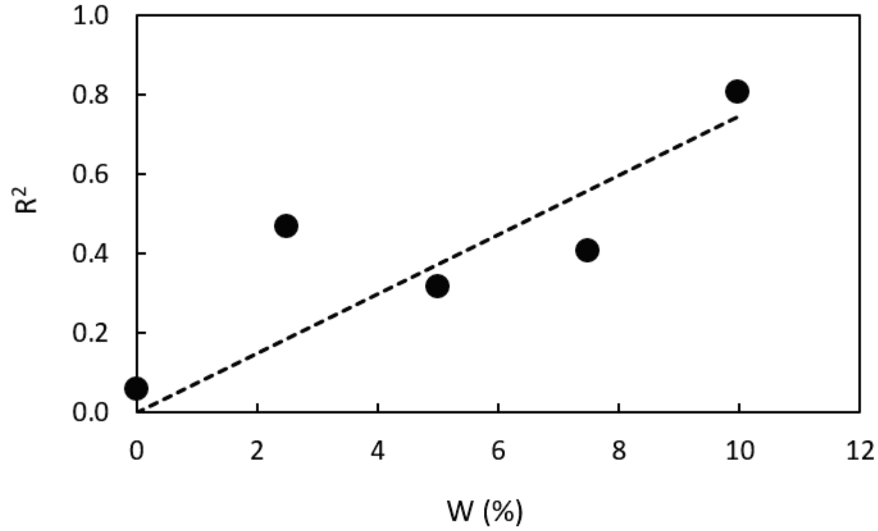

Fig. 1.3 R-squared explains the strength of the relationship between the predicted air exchange rate via the heat balance method and the measured value by tracer gas method using N_2O at multi-span greenhouse (4 spans) under different of window aperture (W). The greenhouse floor area was 422 m^2 and roof vents application (Fernandez and Bailey, 1992).

There are several challenges on this method, for instance: the efficacy of this method is influenced by solar radiation quality in a greenhouse; and difficulties in choosing values for parameters, for example, solar heat gain correction factor (Wang and Zhou, 2017), required more sensors to obtain average values of the respective environmental conditions (Takakura et al., 2017), a spherical type sensor should be used to measure solar radiation at the above of the canopy, and also, the shadow effect of direct radiation on a sensor cannot be neglected (Akutsu et al., 2015). Furthermore, it has a better prediction of the ventilation rate under a large ventilation opening area (Fernandez and Bailey, 1992; Baptista et al., 2001). However, it has a problem to predict the ventilation rate at small window aperture (Fernandez and Bailey, 1992; Yasutake *et al.*, 2017), and it should be clarified in advance about this problem. Thus, the reasons mentioned above would affect the accuracy of the HB method for computing the ventilation rate, and it is still a mystery that should be answered.

On the other hand, the water vapor balance method (WVB) uses the water vapor from the evapotranspiration process, and measurements are made of inside and outside greenhouse air specific humidity measured utilizing psychrometers located in a greenhouse. Many authors have been neglected the phenomena of soil evaporation due to the presence of continuous plastic mulch on the soil surface and the condensation within the greenhouse. This method had been previously adopted by (Boulard and Draoui, 1995) in a two-span plastic naturally ventilated greenhouse with roof vents only. It was reported that the water vapor balance method had a good agreement of the ventilation rate value with the TG method using CO_2 and N_2O. Also, Harmanto, Tantau, and Salokhe (2006b) pointed out the water vapor balance method had a better accuracy estimation when the measurement was conducted in such a greenhouse cultivated with mature plants and in smaller ventilation opening area. Moreover, the method had been applied in various type of compartment with a good result, for instance: multi-spans greenhouse type with continuous roof vents only (Boulard and Draoui, 1995; Kittas et al., 2002) and with continuous roof and side vents configuration (Mashonjowa et al., 2010), screen house type (Harmanto, Tantau, and Salokhe, 2006b; Rigakis et al., 2015), and growth chamber (Li et al., 2012).

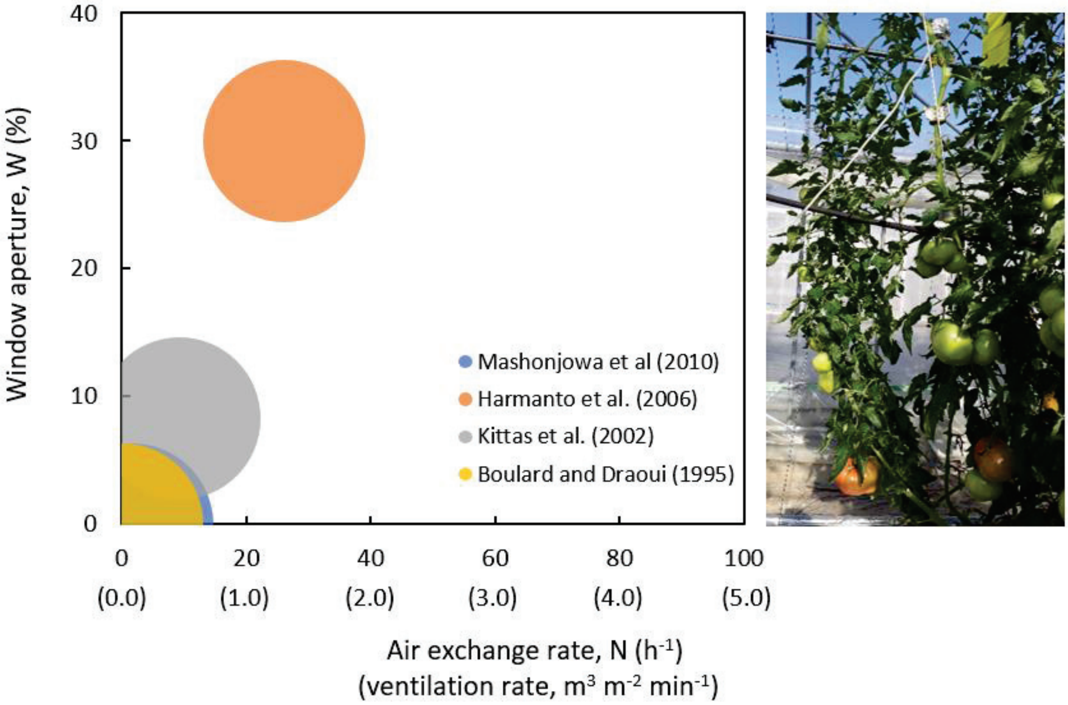

Fig. 1.4 Bubble scattered chart of the air exchange rate using water vapor balance method in a single-span and multi-span greenhouse type cultivated with tomato crops.

Fig. 1.4 illustrates the performance of the water vapor balance method for predicting the air exchange rate (N) in a greenhouse cultivated with tomato plants. The greenhouse types that used are mostly large-scale greenhouses with multi-spans, except for one source from Harmanto et al. (2006b) used screen houses. In general, it is clear that the ventilation rate increases with the ventilation opening area (W). However, most of the air exchange rate performance in this graph was measured under small opening conditions (<10% of W) or ventilation rates below 20 air exchange rates per hour for multi-span greenhouses equipped with the vents, both on the sides and / or above only.

Furthermore, the WVB has a problem in time interval measurement of water vapor generated from crop evapotranspiration. The evapotranspiration is mainly factor that affected the quality of the ventilation rate using this method. Akutsu et al. (2015) noted there was the time lag of direct methods used to measure transpiration. Hence, the time interval for measuring transpiration and choosing of evapotranspiration device should be considered. Harmanto et al. (2006b) recorded average daily transpiration rate with three-time measurements in a screen house type greenhouse. However, continuous monitoring of photosynthesis should be employed in the short-term interval (mostly ranged 5–15 minutes), as mentioned in Fig. 1.2. Thus, it should be considered how to measure and monitor the transpiration in the greenhouse continuously. This condition, moreover, has to be known on a time scale suitable for monitoring of the ventilation rate and the photosynthetic rate.

1.2. Scope, aim, objective and questions of the research

Scope of research

The crucial ventilation in the greenhouse has been recognized for a long period and can be considered as the most critical part of microclimate control for greenhouse engineers. However, the quantification of the ventilation rate was very complicated, and a difficult matter for a long time. The accuracy of the three-type measurement of the ventilation rate is still insufficient. Many questions are still actual, for example concerning the accuracy of the WVB method in large ventilation opening area, and the HB method in a close and small level of ventilation opening area; the accuracy of all methods in different seasons; and validity the ventilation rate value with both methods for predicting the photosynthetic rate due to its not validated yet.

The study was decided to consider just the ventilation rate based on the measurement in a greenhouse, not based on model or simulation in single-span type naturally ventilated greenhouse supported with a double-flap side ventilation and roof ventilation. The greenhouse was cultivated with tomato crops, and the ventilation rates were observed with a three-type measurement of ventilation rate method, namely the tracer gas as a reference, the heat balance method, and the water vapor balance method. Continuous monitoring of the ventilation rate was conducted to estimate the photosynthetic rate via the CO_2 balance method.

Aim and objective of the research

The main goal of the research was to evaluate the accuracy of a three-type measurement method of the ventilation rate in a naturally ventilated greenhouse at various levels of the window aperture.

In detail, the specific objectives of the study were:

a) To evaluate and determine of transpiration measurement instrument that will be used for computing the ventilation rate via the water vapor balance method,
b) To measure the ventilation rate via tracer gas technique in a naturally ventilated greenhouse with no crop condition under various levels of ventilation opening area, as a reference value of ventilation rate.
c) The data collection of ventilation rate under different window aperture (different seasons) will be synthesized to clarify the validity of the heat balance, water vapor balance method as the measuring method of the ventilation rate that compared with the tracer gas method,
d) To construct the graph ratio of heat balance item and absorbed solar radiation in the single-span type greenhouse under different ventilation opening areas for

determining the minimum of window aperture and solar radiation input in the heat balance method.

e) To validate the accuracy of the chosen method for computing the photosynthetic rate with direct measurement of photosynthesis with a portable photosynthesis device (Li-COR).

Questions of the research

After studied the published literature about the ventilation rate through a naturally ventilated greenhouse, the present study found a clearly-defined problem and have formulated more questions as presented in Table 1.3. To answer the research questions formulated in Table 1.3, it was considered essential to collect information on the effect of different window aperture to the ventilation rate in a naturally ventilated greenhouse on tomato crop production.

Table 1.3 Research problem and questions related in a greenhouse ventilation rate

No	Research problem	Research question(s)
1	The measured photosynthesis rate using CO_2 balance and tracer gas technique was validated with an infrared gas analyzer (IRGA). But it is not verified with a direct leaf photosynthesis measurement in a greenhouse.	Do the photosynthetic rate via the tracer gas and CO_2 balance method has the same level value with a direct portable leaf photosynthesis measurement?
2	Most of the researchers used the tracer gas in the CO_2 balance method for computing photosynthesis. Still, it is a lack of information for other ways (the heat balance and the water vapor balance methods) for predicting photosynthesis. The three-type measurement method of the ventilation rate, i.e., the tracer gas, the heat balance method, and the water vapor balance, are not comparing directly in the same greenhouse with all methods in different of window apertures. Therefore, the accuracy of the CO_2 balance method with the high accuracy of ventilation rate prediction with varying levels of ventilation should be evaluated.	Do the HB and the WVB have the same accuracy of the ventilation rate value as the TG method?

No	Research problem	Research question(s)
3	The tracer gas is the most widely used ventilation measurement method and showed excellent performance of predicted ventilation rate at leakage and low ventilation conditions. However, there is a lack of information on tracer gas applications at the maximum level of ventilation opening area, like in summer season.	Does the tracer gas method have excellent performance under large level of window aperture?
4	The heat balance gives better results of the ventilation rate for a higher level of ventilation opening area. However, it has a problem to predict the ventilation rate under close and small level.	Why does the heat balance method have poor accuracy at a low level of ventilation opening area? What factors cause this to happen? Then, what are the minimum of ventilation opening area and the solar radiation level that can provide the best result?
5	The water vapor balance method presents an accurately predicted ventilation rate in a greenhouse cultivated with mature crops and a small level of ventilation opening area. There is limited information related to the performance of the ventilation rate at the moderate and maximum of the window aperture.	Do the water vapor balance method has excellent performance under a high level of window aperture?
6	Also, the water vapor balance method has the time lag of direct methods used to measure transpiration as the main source of the technique. The time interval for measuring transpiration and choosing of transpiration devices should be considered. Continuous monitoring of photosynthesis should be employed in the short-term range (5-15 minutes). Thus, it should be regarded as how to measure and monitor the transpiration in the greenhouse continuously.	What can a transpiration instrument be used to measure at short time intervals?

1.3. Outline of the thesis

Since the chapters in this thesis are self-contained and based on published and submitted articles, some repetition among chapter sections is inevitable, but this makes the independent reading of the chapters easier.

To evaluate the three-type measurement of ventilation rate in a naturally ventilated greenhouse through various window apertures, the ventilation rate performance was divided into two main categorized of ventilation opening area, i.e., at closed and small opening ventilator, and moderate and large level of ventilation opening area. In **Chapter**

2, the measurement of ventilation rate using the TG method was conducted under different window aperture (from close until maximum opening level) with no crop condition as reference for validating the HB and the WVB approaches. Evaluation and validation of three methods are discussed under moderate and maximum level of ventilation opening area. It focuses on answering question research about the WVB and the TG performances at large ventilation conditions.

Next, in **Chapter 3** analyzed the predicted ventilation rate using the HB method under low solar radiation in winter and early spring seasons. It presents experimental results of low ventilation rates with mature-stage tomato crops in a greenhouse to estimate the accuracy of ventilation rate using the HB and the WVB that compared with the reference method. The graph of the ratio of each heat balance item to absorbed solar radiation in a single-span type greenhouse was proposed to elucidate the problem of the HB method at low ventilation rates. **Chapter 4** presents and validates the WVB method as continuous monitoring measurement of the ventilation rate for estimating the photosynthetic rate using the CO_2 balance method. Also, it compares the result with the direct measurement using a portable Li-COR 6400 photosynthesis measurement device. Finally, **Chapter 5** gives an overall discussion of the study. Emphasis is given on ways of creating operational greenhouse ventilation rate measurements in different seasons and several ventilator levels. Recommendation of transpiration device for measuring the ventilation rate via the WVB method, and also, a suggestion for the future practical application and research needed are given.

CHAPTER 2 Continuous measurement of greenhouse ventilation rate in summer and autumn via heat and water vapor balance methods

This chapter has been accepted for publishing as:
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Abstract

Continuous monitoring of canopy photosynthetic rates in a naturally ventilated greenhouse requires a method of measuring ventilation rates that can record accurate short-term responses throughout the day. It is necessary to clarify the difference between the accuracy and operability of ventilation rate methods. This study evaluated the diurnal-change of ventilation rate measured by the heat balance (HB) and water vapor balance (WVB) methods in the summer and early autumn seasons and compared two methods with the tracer gas (TG) method as a reference. The ventilation rate was determined in a single-span type experimental greenhouse with mature-stage tomato crops under different ventilator configurations to assess the accuracy of the above two methods. The ventilation rates measured via the HB and WVB methods were slightly lower than that measured by the TG method in the greenhouse without crops. However, the ventilation rates obtained using both methods exhibited similar variation trends with time. It is difficult to maintain high concentrations of TG in a greenhouse with a large ventilation opening area. However, it was easy to continuously measure the ventilation rate even in such a greenhouse using the HB and WVB methods. Practically, the WVB system is simpler than the HB method, which utilizes numerous sensors.

2.1. Introduction

One of the methods of increasing tomato production and quality in a greenhouse is to manage the CO_2 concentration at or above the ambient level for supporting photosynthesis. CO_2 fertilization enables plants to assimilate CO_2 gas with high efficiency (Kuroyanagi et al., 2014) and increases fruit yield (Kimball and Mitchell, 1979; Yelle et al., 1990). Attention has also been focused on a method of applying CO_2 to a similar level as the outside air in the greenhouse during the daytime in summer or autumn when the windows are sufficiently opened for temperature control (Ohyama et al., 2008). Furthermore, the continuous measurement of the greenhouse ventilation rate throughout the year allows for the long-term direct monitoring of the canopy photosynthetic rate and CO_2 use efficiency using the CO_2 balance method (Nederhoff and Vegter, 1994).

The ventilation rate is a crucial parameter for heat and gas exchanges in a greenhouse. Ventilation regulates the air temperature and humidity in the greenhouse. Additionally, it influences CO_2 concentration, which affects the canopy photosynthetic rate. Various techniques have been used to measure and predict the ventilation rate, such as the tracer gas (TG) method (Boulard and Draoui, 1995; Papadakis et al., 1996; Baptista et al., 1999), heat balance (HB) method (Fernandez and Bailey, 1992; Demrati et al., 2001; Harmanto et al., 2006a), and water vapor balance (WVB) method (Boulard and Draoui, 1995; Harmanto et al., 2006a, 2006b). The TG method has been widely used in greenhouse experiments. The ventilation rate measurement by the TG method is highly reliable in leakage and low ventilation conditions for different types of greenhouse and ventilation configurations (Nederhoff et al., 1985; Baptista et al., 1999; Muñoz et al., 1999; Katsoulas et al., 2006). The TG method exhibits good agreement with an infrared gas analyzer (IRGA), as mentioned by Nederhoff et al. (1985), and with a theoretical model based on pressure difference (Baptista et al., 1999) and wind pressure model approaches (Muñoz et al., 1999).

However, in the summer season with the maximum ventilation opening area, the TG method experiences numerous disadvantages in large-scale greenhouses (Demrati et al., 2001). A large amount of CO_2 gas must be supplied to maintain the CO_2 concentration in a greenhouse higher than outside air for a large window aperture. Moreover, this method is expensive, and the long-term continuous measurement of the ventilation rate is extremely difficult under plant cultivation, where CO_2 gas is absorbed. Hence, it may not be possible to use this technique for the continuous monitoring of the ventilation rate in summer and autumn season when windows are fully opening during the daytime.

There are two alternative methods of predicting the ventilation rate, i.e., the HB (Fernandez and Bailey, 1992; Katsoulas et al., 2006; Yasutake et al., 2017) and WVB techniques (Boulard and Draoui, 1995; Kittas et al., 2002; Mashonjowa et al., 2010). The ventilation rates predicted using the heat balance model showed good agreement with measured values using the TG method for large ventilation opening areas (Fernandez and Bailey, 1992; Baptista et al., 2001). However, there is a problem when the ventilation opening area is small (Yasutake et al., 2017). On the contrary, the WVB method provides better accuracy in estimating the ventilation rate for mature plants under small ventilation opening areas (Boulard and Draoui, 1995; Harmanto et al., 2006b). Most of the authors performed at low ventilation (i.e., with 10% of window aperture or below 20 h^{-1} of the air exchange rate) for the multi-span greenhouse (Boulard and Draoui, 1995; Kittas et al., 2002; Mashonjowa et al., 2010). Harmanto et al. (2006b) calculated the ventilation rate using the WVB method under various screen mesh size on the wall of the greenhouse with three times measurement of water vapor from the crops every day. However, few studies have investigated the ventilation rate performance using the WVB method at moderate and maximum window openings, especially in a single-span type greenhouse. Therefore, the accuracy of estimating the ventilation rate using the WVB method for large ventilation opening areas must be examined in detail. As described above, the accuracy of the ventilation rate measurement of the naturally ventilated greenhouse by the HB and

WVB method has not been sufficiently verified by the influence of the window opening area. However, both methods are more suitable than the TG method for long-term continuous measurement of the ventilation rate of a cultivated greenhouse with large opening windows.

The purpose of this research is to clarify the validity of the HB method and the WVB method as the measuring method of the ventilation rate, which is required for continuous monitoring of the canopy photosynthetic rate in a naturally ventilated greenhouse during the cultivation period. First, we measured the ventilation rate via the TG method using CO_2 as a standard reference at various window apertures with no crop cultivation. Next, we evaluated the diurnal change of ventilation rate measured by the HB method and WVB method under the greenhouse mentioned above with cultivating plants and compared it with the value of the TG method.

2.2. Materials and methods

Greenhouse experiment set up

An experiment was performed in a single-span greenhouse at a research field site of the Faculty of Applied Biological Sciences, Gifu University, Japan. The greenhouse was fabricated from glass (glasshouse) with dimensions of 3.25 m in width × 5.00 m in length × 2.80 m in height. It had a supported roof and double-flap side vents, which were covered with screen-net materials (pore size of 0.4 mm and porosity of 52.2%). The experiment was performed for different values of the ventilation opening area, which was expressed in terms of the W value in percentage. The W value was calculated based on the ratio of the total ventilation opening area to the greenhouse floor area (Eq. 2.1). In this experiment, the W value was obtained under moderate and maximum ventilation as 16%, 20%, 24%, and 40% in the summer and early autumn seasons. The ventilation rate was measured under constant of the W value on the day experiment.

$$W = \frac{Total\ window\ opening\ area\ (m^2)}{Greenhouse\ floor\ area\ (m^2)} \times 100 \qquad (\%) \qquad (2.1)$$

The greenhouse was occupied by mature fruiting tomato crops (*Solanum lycopersicum L.*,variety 'Momotaro'), which were cultivated on 14 modified Wagner pots with a volume of 10 L (one plant per pot). The pots were filled with light sandstones (diameters ranging from 1 to 5 mm) and supplied with hydroponic nutrient solutions (electrical conductivity, EC = 1 dS m^{-1}, and pH = 5.5–6.5) in the lower part of the pot system with a maximum water level of 10 cm (capillary irrigation system). The growing medium in the pot system was covered with plastic mulch. During the measurement periods in summer 2018 and early autumn 2019, the average height of tomato plants was approximately 1.6 m, and the leaf area index of the crop was approximately 3.8 m^2 m^{-2}. The plants were placed 0.45 m apart in double rows, with an inter-row distance of 0.80 m.

The following climatic data were recorded: air temperature inside and outside (dry and wet bulb temperatures) the greenhouse, solar radiation inside and outside the greenhouse, and wind velocity outside the greenhouse. Figure 2.1a shows the location of instrumentation sensors in the greenhouse. Air temperature (dry and wet bulb temperatures) was measured by two aspirated psychrometers using T-type thermocouple (copper/constantan) sensors. The psychrometers were set up at heights of 0.5 m and 2.0 m above the floor at the center of the greenhouse. The aforementioned data were recorded in a data logger (CR1000, Science Campbell, USA) every minute. Then, the ventilation rate was calculated based on the average data for 15 min over a long period (from 8:00 AM to 4:00 PM).

Determination of the ventilation rate

The air exchange rate, or ventilation rate, in the naturally ventilated greenhouse was estimated using two approaches, namely, the WVB and HB methods.

Only the water vapor that originated from the crop transpiration in the growth process was considered, and the evaporation from the pot medium and greenhouse floor were neglected because they were covered with plastic mulch. The assumption had been made that water vapor transpired from each plant was uniform for all points in the greenhouse, and the amount of water to be evaporated should be equivalent to the amount of water vapor removed by ventilation. Thus, a steady-state condition was assumed in the greenhouse because the changes in the amount of water vapor in a short period of time were small. The crop transpiration rate was directly measured by employing two stem heat balance sensors (Model SGA13-WS, Dynamax Inc., USA). Then, the average estimated evapotranspiration was converted to a unit land area basis by multiplying it with the number of plants and adding a plant coverage factor to the total greenhouse floor area (Eq. 2.2). The plant coverage factor was measured from the real horizontal projection of the canopy, as performed by Gerson et al. (2001). The following equation was used to calculate the ventilation rate using the WVB method:

$$G_{\mathrm{WVB}} = \frac{nE}{A_{\mathrm{f}}\, F_{\mathrm{ca}}\, [AH_{\mathrm{in}} - AH_{\mathrm{out}}] \times 60} \qquad (2.2)$$

where G_{WVB} is the measured ventilation rate per unit floor area of the greenhouse over a period [$\mathrm{m^3\ m^{-2}\ min^{-1}}$]; n is the total number of plants; E is the measured transpiration per plant [$\mathrm{g\ h^{-1}}$]; A_{f} is the greenhouse floor area [$\mathrm{m^2}$]; F_{ca} is the ratio of the total plant coverage area to the greenhouse floor area; and $AH_{\mathrm{in}} - AH_{\mathrm{out}}$ [g m^{-3}] is difference between the absolute humidity inside and outside the greenhouse over a period.

In the HB method, it is considered that ventilation removes energy from a greenhouse and prevents excessively high temperatures. The HB method assumes a steady-state condition and uses the principle of energy conservation, i.e., heat gains are equal to heat losses inside and outside a greenhouse. No heating is used, and the energy removed by leakage (under the closed vents condition) and ventilation (Q_{v}) is equal to the net solar radiation collected in the greenhouse (Q_{Rn}) minus the energy stored in soil (Q_{s}), and the thermal losses through the cover (Q_{c}). The energy stored in soil was measured every minute by a soil heat flux sensor that was placed 10 mm below the ground surface. The equations for the static energy balance of a naturally ventilated greenhouse have the following general form:

$$Q_{\mathrm{v}} = Q_{\mathrm{Rn}} - Q_{\mathrm{s}} - Q_{\mathrm{c}} \tag{2.3}$$

$$Q_{\mathrm{Rn}} = (1 - \alpha)\,\tau\,R_{\mathrm{so}} - \sigma\,T_{\mathrm{in}}{}^{4}\,(\varepsilon_{\mathrm{a}} - \varepsilon_{\mathrm{c}}) \tag{2.4}$$

$$Q_{\mathrm{c}} = k(T_{\mathrm{in}} - T_{\mathrm{out}})\frac{A_{\mathrm{c}}}{A_{\mathrm{f}}} \tag{2.5}$$

$$G_{\mathrm{HB}} = \frac{Q_{\mathrm{V}}}{[c_{\mathrm{p}}\cdot\rho_{\mathrm{a}}\cdot(T_{\mathrm{in}} - T_{\mathrm{out}}) + L_{\mathrm{v}}\cdot(AH_{\mathrm{in}} - AH_{\mathrm{out}})]} \times 60 \tag{2.6}$$

where G_{HB} is the measured ventilation rate per unit floor area over a period [m^{3} m^{-2} min^{-1}]. Q_{Rn} is the average incoming net solar radiation inside the greenhouse during the day [W m^{-2}]. It is calculated based on the total solar radiation (R_{so}) outside the greenhouse, with α as the ground surface albedo. τ is the coefficient of solar radiation transmittance of the glazing material (dimensionless), σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and ε_{a} and ε_{c} are atmospheric air emissivity and crop emissivity, respectively. ε_a was computed using the model developed by Idso (1981), and ε_c for tomato crop was used as Pieters and Deltour (1997). Q_s is the soil heat flux [W m^{-2}]; Q_c is the heat transfer through the greenhouse cover; and Q_v is the heat removed via ventilation [W m^{-2}]. k is the heat transmittance coefficient of the greenhouse cover [W m^{-2} K^{-1}]; in this experiment, the value of k was 6.0 W m^{-2} K^{-1} for single glass. A_c is the covered area of the greenhouse [m^2]; c_p is the specific heat capacity of air [J kg^{-1} K^{-1}]; ρ_a is the specific mass of air [kg m^{-3}]; $T_{\text{in}} - T_{\text{out}}$ is the difference between the air temperature inside and outside the greenhouse [K]; and L_v is the latent heat of vaporization [J kg^{-1}]. The value of 60 is introduced as a factor to convert the unit of time from seconds to minutes.

Prediction of ventilation rate

Table 2.1 shows the periods and window apertures for which the ventilation rate was measured in the summer and early autumn seasons using the WVB and HB methods. Furthermore, the ventilation rate was measured via the TG technique in the same greenhouse without crops in April and May 2019. An equation was made from the window aperture and the ventilation rate with simple linear regression, and then, the predicted ventilation rates were compared and validated using it.

Table 2.1 Ventilation rates observed in different seasons

Season	Date of experiments	W (%)
Summer	July 10–11, 2018	16%
	July 19– 20, 2018	20%
	July 22– 23, 2018	24%
Autumn	September 16, 17, 19, and 25, 2019	40%

The ventilation rate was obtained using the WVB and HB method every minute and then averaged over an interval of 15 min. The ventilation rate was measured using the TG technique every second and then averaged over an interval of 15 min. The ventilation rate measurement using the TG method with CO_2 gas was conducted based on the method proposed by Nederhoff et al. (1985); however, the CO_2 concentration was modified. In the experiment, nine CO_2 sensors (Model K30, Senseair Co., Sweden) were installed inside the greenhouse, one on the side vents, and one outside the greenhouse (Fig. 1a). CO_2 gas was injected into the greenhouse until a concentration of 550 ppm was reached, and then, the supply was stopped. As a result of an exchange with outside air, the CO_2 concentration in the greenhouse decreased with a rate proportional to the difference between the CO_2 concentration inside and outside the greenhouse. When the CO_2 concentration decreased to 450 ppm, CO_2 was injected again to increase the concentration to 550 ppm (Fig. 2.1b). The ventilation rate obtained using the TG technique (G_{TG}) is given by the following equations:

$$N_{\mathrm{TG}} = \frac{3600}{t_1}\, ln \left[\frac{C_{\mathrm{in}}(t_0) - C_{\mathrm{out}}}{C_{\mathrm{in}}(t_1) - C_{\mathrm{out}}}\right] \qquad (2.7)$$

$$G_{\mathrm{TG}} = \frac{1}{60}\,\frac{N_{\mathrm{TG}}\, V_{\mathrm{g}}}{A_{\mathrm{f}}} \qquad (2.8)$$

where $C_{\mathrm{in}}(t_0)$ is the initial CO_2 concentration at $t = 0$, $C_{\mathrm{in}}(t_1)$ is the CO_2 concentration measured at $t = t_1$, and V_{g} is the greenhouse volume (m^3). The value of 3600 is introduced as a factor because the greenhouse air exchange rate (N_{TG}) is expressed as times per hour of greenhouse volume exchange (expressed in h^{-1}) and t is in seconds. The greenhouse air exchange rate per hour (N_{TG}) can be converted to the ventilation rate, G_{TG} ($\mathrm{m}^3\ \mathrm{m}^{-2}\ \mathrm{min}^{-1}$), using Eq. 2.8.

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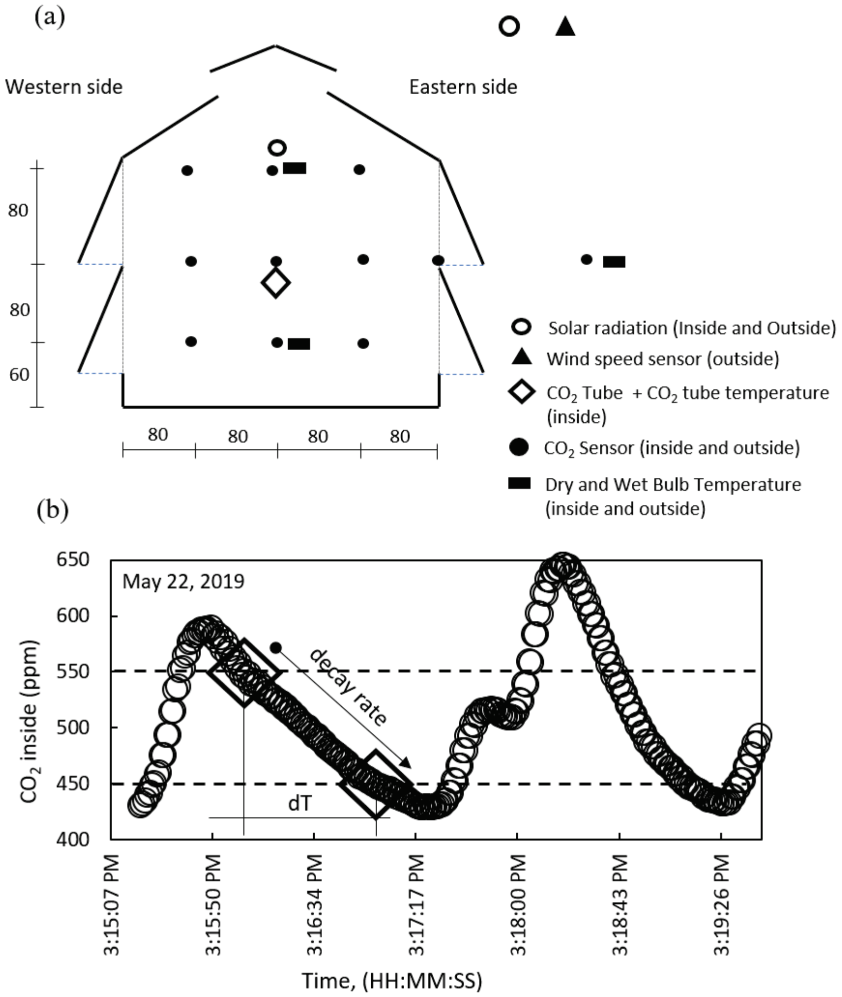

Fig. 2.1 Schematic of cross-sectional views, ventilator, and locations of instrumentation in the experimental greenhouse. (a) Location of all sensors: dry and wet bulb temperatures (inside and outside), CO_2 (inside and outside), CO_2 tube temperature, solar radiation (inside and outside), and wind speed (outside). All dimensions are in cm. (b) Ventilation rates measured using the tracer gas technique. The decay rate method is used with CO_2 concentration maintained between 450–550 ppm without crops. dT: time length of decay rate.

2.3. Results and discussion

Figure 2.2 shows the relationship between G_{TG} and W in the greenhouse without crops, and the linear regression equation with W as an independent variable is as follows:

$$G_{\mathrm{TG}} = 0.132 \times W + G_0 \quad (2.9)$$

with a coefficient of determination $R^2 = 0.83$ (p-value = 2.2×10^{-16}).

The G_{TG} at leakage condition, G_0 ($W = 0\%$) was 0.052 $m^3 m^{-2} min^{-1}$ (N_{TG}: 1.3 h^{-1}). The maximum of N_{TG} was 140 h^{-1} when W was 40%. Simultaneously, the range of variation in the measured ventilation rate also increased with W. This was probably because the effect of outside wind on the ventilation rate became stronger as the window aperture increased. During the experimental period, the average wind speed outside the greenhouse was 0.9 m s^{-1} (0–3.1 m s^{-1}), and the average CO_2 concentrations inside and outside the greenhouse were 514 and 393 ppm, respectively (Table 2.2). Eq. 2.9 and Fig. 2.2 could be used as a reference for validating the ventilation rate predicted using the HB and WVB methods.

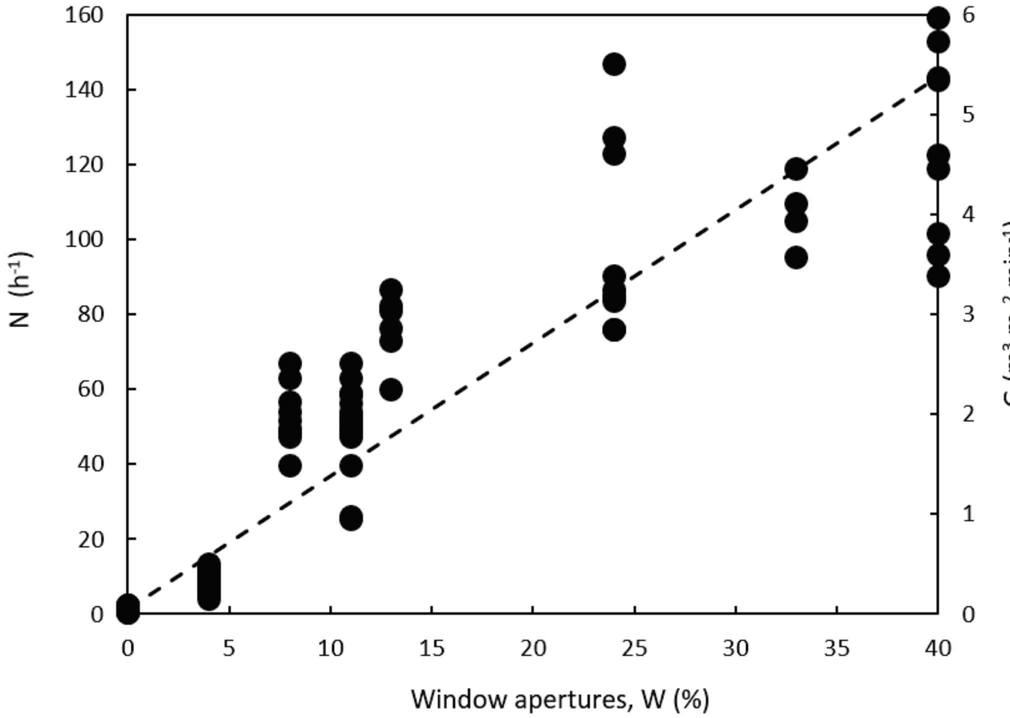

Fig. 2.2 Ventilation rates measured using tracer gas technique without crops on several days (April 27 and May 2, 5, 8, and 22, 2019). Data are averaged every 15 min. 4–18 data measurements (n) are obtained for each window aperture (total of 84 observations). ***P = $2.2 \times 10^{-16} < 0.01$.

Table 2.2 Climatic conditions during observation of ventilation rate using tracer gas (no crops)[a]

W %	Q_{Rn} W m^{-2}	v m s^{-1}	$(T_{in}–T_{out})$ °C	VPD kPa	CO_{2in} ppm	CO_{2out} ppm
0	112–625[b]	0.4–2.6	7.8–12.8	0.3–2.9	465–668	373–409
	338[c]	1.4	10.3	1.3	556	389
4	23–800	0.2–1.1	3.1–11.8	0.3–4.3	496–566	379–409
	291	0.5	8.6	2.2	519	393
8	136–636	0.6–1.3	4.3–5.8	0.4–0.6	497–514	378–380
	362	0.9	5.1	0.5	503	379
11	136–815	0.1–2.7	4.2–7.6	0.2–2.4	492–517	378–405
	385	1.0	5.6	0.6	504	382
13	184–569	0.4–0.9	2.8–3.8	0.3–0.4	503–519	380–384
	470	0.7	3.2	0.3	512	383
24	527–805	0.8–1.0	2.5–2.8	1.7–1.9	520–523	409–412
	666	0.9	2.7	1.8	521	411
33	127–488	0–0.8	3.7–5.4	1.6–1.8	491–515	407–413
	240	0.4	4.7	1.7	499	410
40	249–815	0.3–3.1	1.7–6.8	0.2–2.3	475–513	382–412
	548	1.4	3.7	1.2	497	397
Average	413	0.9	5.5	1.2	514	393

W: window aperture, Q_{Rn}: solar radiation inside greenhouse, *v*: wind speed outside greenhouse, $(T_{in} – T_{out})$: difference temperature between inside and outside greenhouse, *VPD*: vapor pressure deficit, CO_{2in} and CO_{2out}: CO_2 concentration in inside and outside, respectively.
a) Climatic conditions during observation on April 27 and May 2, 6, 8, and 22, 2019.
b) Data range from minimum to maximum.
c) Average data for each window aperture.

The G_{HB} and G_{WVB} methods showed similar variation trends with time, and the ventilation rate changed considerably with the wind speed outside the greenhouse. The change in the ventilation rate for the large ventilation opening area (September 16, 2019) was higher than that for the moderate ventilation opening area (July 22, 2018), even with the same amount of absorbed solar radiation. A high ventilation rate reduced ΔT and Δh

to a larger extent compared with a low ventilation rate. Increased solar radiation affects the climate condition in a naturally ventilated greenhouses. Thus, ventilation systems are a crucial part of maintaining the optimal environment for crop cultivation. In summer, it is better to open vents to the maximum level because the ΔT increases to above 4 °C (at $W = 24\%$), as shown in Fig. 3a. Therefore, it is better to keep a high ventilation rate in the summer and should be measured continuously at short intervals to consider the effect of external climate conditions.

The maximum ventilation rate at $W = 24\%$ was approximately 3.6 $m^3\ m^{-2}\ min^{-1}$ and 3.2 $m^3\ m^{-2}\ min^{-1}$ at midday (between 12:00 and 14:00) under a high solar radiation of almost 500 W m^{-2}. In contrast, at $W = 40\%$, the ventilation rate was the maximum at 5.4 $m^3\ m^{-2}\ min^{-1}$ and 4.9 $m^3\ m^{-2}\ min^{-1}$ for the HB and WVB methods, respectively. At moderate and maximum ventilator openings, the average G value obtained using the WVB was slightly lower than the HB method. Furthermore, the G value via the TG method was higher than the HB and the WVB at the maximum level of W (Fig. 2.4). Yasutake et al. (2017) reported the maximum value of air exchange rate (N) by the CO_2 balance method between 5 – 7 h^{-1} at 20% of W in the midday, whereas the gas method was slightly higher than the heat balance method. They noticed a small value of N due to a different size of greenhouse (a single-span greenhouse, 150 m^2 of floor area, without crops condition). In this paper, a slightly lower value of G_{HB} and G_{WVB} was because of gas diffusion resistance owing to the tomato plant canopy in the greenhouse during the measurement. However, the average ventilation rates obtained via both measurement methods were equivalent for each ventilation opening area. In addition, the ventilation rate increased gradually as the window aperture increased from 16% to 40% (Fig. 2.5).

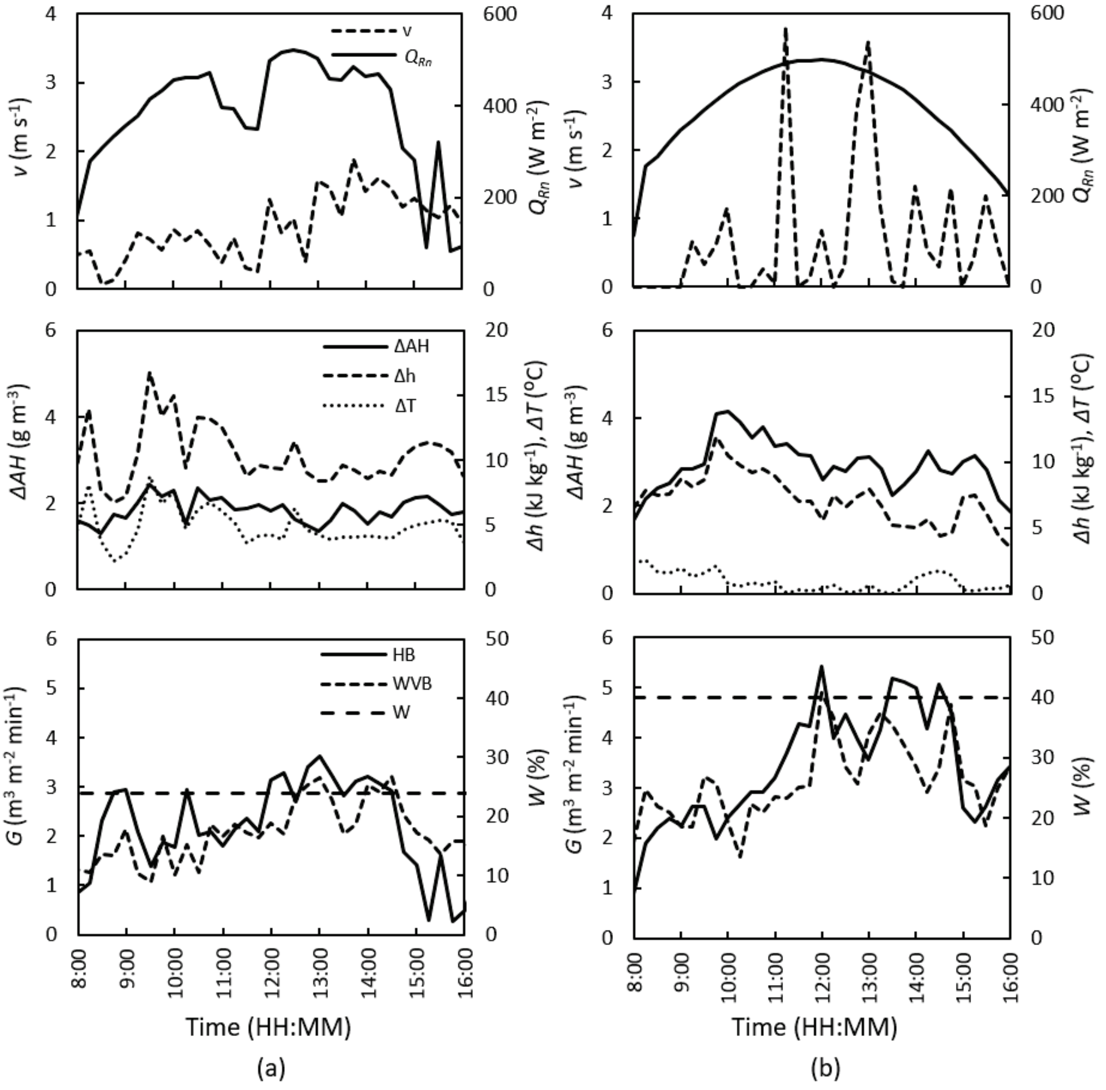

Fig. 2.3 Time series of the ventilation rate (G) obtained using the HB and WVB methods at different window apertures (W). (a) Moderate and (b) large apertures. v: outside wind speed, Q_{Rn}: solar radiation absorbed in the greenhouse, ΔAH: difference of absolute humidity between inside and outside, Δh: difference of enthalpy inside and outside, and ΔT: temperature difference inside and outside greenhouse. The measurements for the moderate and large window apertures were performed on July 22, 2018 and September 16, 2019, respectively. Tomato plants were cultivated by substrate culture in the greenhouse.

The aforementioned results confirmed that the HB method provided accurately predicted the ventilation rate not only for the maximum window aperture, as mentioned by Fernandez and Bailey (1992), but also for the moderate window aperture (approximately 16–24%), as presented in Fig. 2.5. The HB method gave better results for moderate and higher ventilator openings under high radiation conditions. In the experiment, the average absorbed solar radiation during the observation was above 200 W m^{-2}.

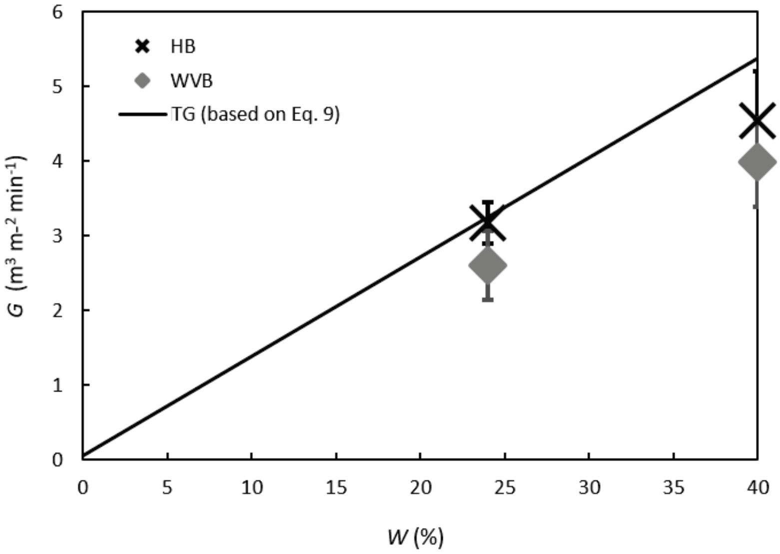

Fig. 2.4 The average ventilation rate (G) at midday (between 12:00 and 14:00) measured using the HB method (×) and WVB method (◊) under window aperture (W) 24% and 40%. The data are presented as means with standard deviations. The line graph showed the ventilation rate using the TG method without crop condition.

The ventilation rate obtained using the WVB method exhibited good correlation and agreement with that obtained using the HB method, with the Pearson correlation coefficient (r) = 0.913, as presented in Fig. 2.6 (ventilation rate in a range of 1–5 m^3 m^{-2} min^{-1}). The results performed the ability of the WVB method that can predict the ventilation rate not only under a small ventilation opening area (Boulard and Draoui, 1995) but also until a high level of the window aperture. The cultivation period of greenhouse tomato production is long, ranging from early autumn to early summer of the following year in Japan. The ventilation opening area changes depending on the season owing to air temperature control. Therefore, the WVB method is suitable for the long-term continuous measurement of the ventilation rate under different window apertures.

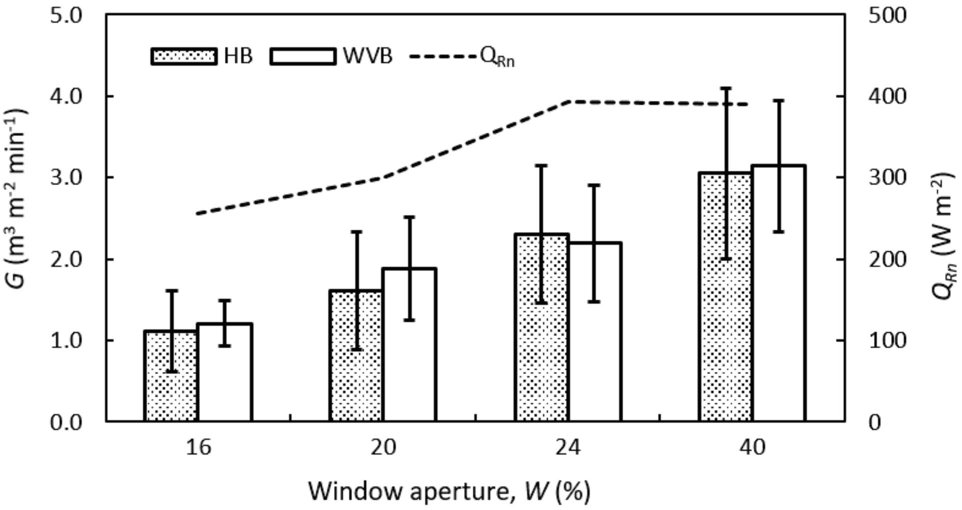

Fig. 2.5 Average ventilation rate (G) measured using the HB method (shaded bars) and WVB method (white bars) for W =16%–40%. The data are presented as means with standard deviations. The dashed line shows the average of the net radiation inside the greenhouse (Q_{Rn}).

The TG method is extremely reliable for measuring ventilation rates for various ventilation opening areas. However, when for a large ventilation opening area, a considerable amount of TG is required to maintain high and uniform concentration in a greenhouse. Furthermore, it is difficult to maintain a uniform CO_2 concentration in the greenhouse because the outdoor airflow affects the CO_2 concentration distribution in the greenhouse. One of the solutions to this problem is to set numerous measurement points of CO_2 concentration in the greenhouse (Romanini et al., 2012). However, sophisticated technology with large memory is required because data must be recorded at short intervals (every second). Furthermore, a large number of sensors is necessary for achieving good accuracy. Practically, it is quite difficult to implement the TG method for continuously monitoring the ventilation rate because of the above reasons and high cost. The results obtained in this study show that the HB and WVB methods can be used for monitoring the ventilation rate for moderate and large ventilation opening areas.

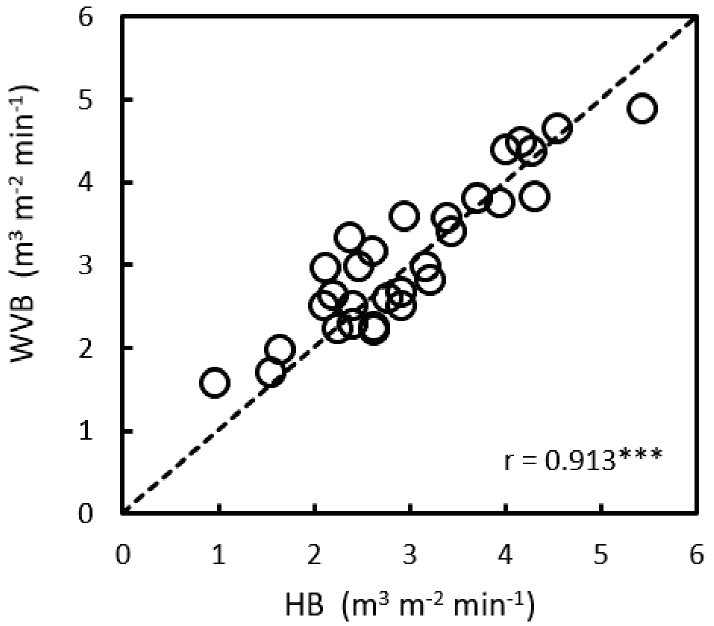

Fig. 2.6 Relationship between the ventilation rates obtained using the HB and WVB methods. Each value represents the mean of the values calculated every 15 min in the naturally ventilated greenhouse on September 16, 19, and 25, 2019, for a window aperture of 40%. The dashed line indicates the targeted line, and the corresponding value of the Pearson correlation coefficients (r) is presented in the figure (***$P = 2.13 \times 10^{-12} < 0.01$).

2.4. Conclusion

In conclusion, the ventilation rate was measured using the HB and WVB methods for moderate and maximum window apertures in a naturally ventilated greenhouse. The measured ventilation rate was compared with the ventilation rate obtained using the TG technique as a reference. The ventilation rates measured by the HB and WVB methods exhibited similar variation trends with time. Furthermore, the WVB method was simpler than the HB method because the WVB method had fewer measurement parameters. Overall, the WVB method was demonstrated to be a potentially useful tool for the continuous measurement of the ventilation rate.

CHAPTER 3 Comparison of three ventilation rate measurement methods under different window apertures in winter and spring

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Abstract

Ventilation rate is one of the essential parameters for continuous monitoring of the photosynthetic rate via the CO_2 balance method. Diurnal changes in the ventilation rates (*G*), measured using the heat balance (HB) and water vapor balance (WVB) methods during winter and spring in a naturally ventilated greenhouse with tomatoes cultivation were compared indirectly with the tracer gas (TG) method as a reference. The *G* obtained through both methods increased in response to changes in window opening (*W*). However, when the *W* changed rapidly in a short time, the response of the *G* measured using the HB method was delayed compared with that of the *G* obtained using the WVB method. The *G* via the WVB method performed similarly to the TG method at small *W*, and to the HB method at moderate *W*. Further, the change in *G* measured using the HB method was sensitive to solar radiation. Meanwhile, the *G* measured using the WVB method exhibited a stable response to changes in *W* and could permit continuous real-time monitoring of greenhouse ventilation rates, as is needed to estimate the photosynthetic rate for all of the plants in a greenhouse.

3.1. Introduction

Real-time photosynthetic rate monitoring is crucial for managing crop cultivation in greenhouses. Nederhoff and Vegter (1994) presented a canopy photosynthesis measurement method that enabled the accurate estimation of the greenhouse CO_2 balance. The ventilation rate affects not only the air temperature and humidity in a greenhouse, but also the photosynthesis of the cultivated plants. Takakura et al. (2017) proposed a method of directly estimating the canopy photosynthetic rate by introducing the ventilation rate estimated from the greenhouse environmental parameters into the CO_2 balance equation. The ventilation rate measurement is a very complex mechanism including heat transfer processes of conduction, convection, and radiation occurring in a naturally ventilated greenhouse. Also, the ventilation rate was influenced by the presence of crops, the structure and design of the greenhouse, and was constantly fluctuating throughout the day (Mashonjowa et al. 2010). Therefore, it is necessary to measure the ventilation rate in the cultivation greenhouse continuously.

Various ventilation rate measurement techniques have been studied extensively, such as the tracer gas (TG), heat balance (HB), and water vapor balance (WVB) methods. The TG and HB methods are the most widely adopted for greenhouse ventilation rate measurement (Fernandez and Bailey 1992). In previous research, the TG technique has exhibited highly accurate air exchange rate measurement under leakage conditions (i.e., with the window aperture closed) and with the smallest window aperture (Fernandez and Bailey 1992; Nederhoff et al. 1985; Baptista et al. 1999; Muñoz et al. 1999). Meanwhile, other studies have shown that the HB method achieves high accuracy with larger ventilator openings (Fernandez and Bailey 1992; Baptista et al. 2001). The WVB method was found to estimate the ventilation rate more accurately than the TG method under small ventilator opening areas (Boulard and Draoui 1995) and was performed in a greenhouse cultivated with mature plants (Harmanto et al. 2006).

In addition, the TG method is not suitable for long-term, continuous ventilation rate measurement (Sherman 1990) because it requires a large amount of TG in a cultivated greenhouse and SF_6, which is used as a TG, is expensive. Meanwhile, the HB technique requires numerous variables for ventilation rate measurement even if continuous measurement in a greenhouse is possible (Baptista et al. 1999). There are also some challenges regarding the WVB method related to i) direct measurement of the transpiration rate, which is one of the parameters, using a lysimetric device (Kittas et al. 2002); ii) overestimation of the ventilation rate at night (Mashonjowa et al. 2010); and iii) evaluation of the error in the evapotranspiration rate, which increases when scaling up from a few plants to the whole canopy (Mashonjowa et al. 2010; Boulard and Draoui 1995).

We have been working on the measurement of the ventilation rate, which is one of the essential parameters suitable for direct and continuous prediction of the photosynthetic rate for all of the cultivated plants by using the CO_2 balance method in a naturally ventilated greenhouse. Since the protected cultivation of tomato plants occurs from early autumn to early summer of the following year in Japan, the opening area of the greenhouse windows is adjusted depending on the climatic conditions. Thus far, a comparison of the investigated ventilation rate measurement in different seasons has never been reported previously. In this study, the diurnal change in the ventilation rate was continuously measured using the HB and WVB methods in a naturally ventilated greenhouse with cultivated tomato plants during the winter and spring, and the validity of the results was evaluated by comparing the measured ventilation rates with those obtained using the CO_2 TG method as a reference indirectly.

3.2. Materials and methods

Greenhouse experiment setup

This experiment was performed in the spring (April 20–22, 2019) and winter (December 12–19, 2019) on a single-span greenhouse at a research field site of the

Faculty of Applied Biological Science, Gifu University, Japan. The greenhouse was composed of glass (glasshouse) with dimensions of 3.2 m × 5.0 m × 2.8 m. It had a supported roof and double flap side vents, which were covered with screen-net material (pore size 0.4 mm and porosity 52.2%). The experiment was performed with the upper side vents and roof vents (SV2-RV1) open in spring and only the roof vents (SV0-RV1) open in winter, as shown in Fig. 3.1. The window aperture (W) was presented as a percentage calculated based on the ratio of the total ventilation area to the greenhouse floor area (Eq. 3.1). The ventilation opening area was controlled automatically based on the inside air temperature with a five-stage opening angle (S0, S1, S2, S3, and S4) with temperature set points of 20 °C and 25 °C in winter and spring, respectively (Table 3.1). The W values for ventilation SV2-RV1 treatment were 0, 3, 7, 12, and 16%; and SV0-RV1 ventilation combination were 0, 2, 4, 6, 13% for S0, S1, S2, S3, and S4, respectively.

$$W = \frac{Total\ window\ opening\ area\ (m^2)}{Greenhouse\ floor\ area\ (m^2)} \times 100\% \qquad (3.1)$$

The greenhouse had mature fruiting tomato crops (*Solanum lycopersicum L.*, variety “Momotaro”), cultivated in 14 modified Wagner pots with a volume of 10 L (one plant per pot) filled with light sandstone (diameter 1–5 mm) and supplied with hydroponic nutrient solution (EC = 1 dS m^{-1} and pH 5.5–6.5) in the lower part of the pot system with a maximum water level of 10 cm (capillary irrigation system). Plants were fertilized with a complete nutrient solution - stock A (10% N, 8% P_2O_5, 27% K_2O, 4% MgO, 0.10% MnO, 0.10% B_2O_3, 0.18% Fe, 0.002% Cu, 0.006% Zn, and 0.002% Mo) and stock B (11% N, and 16.4% Ca) – after transplanting to the production system. The growing medium in the pot system was covered with plastic mulch. During the measurement periods in the spring and winter, cultivated tomato plants with an average height of about

1.6 m were managed, and the leaf area index (LAI) of the crop was about 3.8. The plants were laid out 0.45 m apart in double rows and with an inter-row distance of 0.80 m.

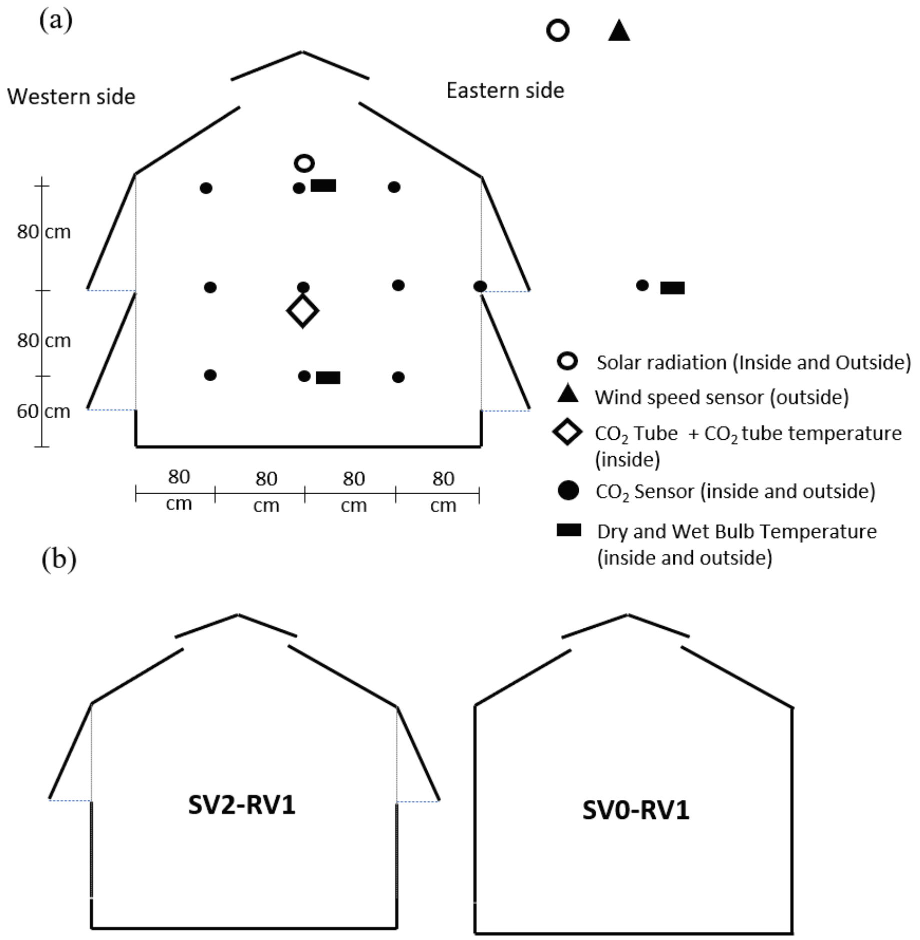


Fig. 3.1 Schematic diagrams of cross-sectional views, ventilators, and locations of instrumentation in the experimental greenhouse. (a) Locations of sensors for dry and wet bulb temperatures, CO_2, solar radiation (inside and outside), and outside wind speed. (b) Opening window treatments: upper side and roof vents used in spring (SV2-RV1) and roof vents used in winter (SV0-RV1).

The following climatic data were recorded: greenhouse air temperatures both inside and outside (dry and wet bulb temperatures), inside and outside solar radiation above the top of the crops, and outside wind velocity. The air temperatures (dry and wet bulb temperatures) were measured by two aspirated psychrometers using T-type thermocouple (copper/constantan) sensors. Two psychrometers were set up at heights of 0.5 m and 2.0 m above the floor in the center of the greenhouse. Two pyranometers (Model MS-602, EKO Instruments, Japan) were placed inside and outside the greenhouse at 1.8 m and 3.5 m above the ground, respectively. All the above measurements were recorded by a data logger (CR1000, Science Campbell, USA) in 1 min intervals. The transpiration rate and microclimate conditions were measured for an extended time (from 8:00 to 16:00).

TG method

The ventilation and leakage rates were measured by injecting a TG and then measuring the decay rate of the gas concentration (dynamic TG method). The TG CO_2 was supplied from a gas tube tank by a diffusive tube (2 m long) placed in the middle of the height of the plant. Ten CO_2 sensors (Model K30, Senseair, Sweden) were used inside the greenhouse and one sensor was used outside the greenhouse (Fig. 3.1) to measure the CO_2 concentration level every 1 s. The experiment was performed continuously in the greenhouse without crops on from April 27 to May 22, 2019. The ventilation rate measured using the TG method was conducted with no opening and small ventilation opening areas (W = 0%, 4%, and 12%). Data were collected every 1 s, and the decay rate was averaged in 15 min intervals. The ventilation rate measurement method using CO_2 TG was based on the technique proposed by Nederhoff et al. (1985) with the CO_2 concentration modified. In this experiment, CO_2 gas was injected into the greenhouse until a concentration of 550 μmol mol^{-1} was reached, at which point the supply was stopped. As a result of exchange with the outside air, the concentration in the greenhouse decreased at a rate proportional to the CO_2 difference between inside and outside if the ventilation rate is constant in time. When the CO_2 level had decreased to below 450 μmol mol^{-1}, CO_2 was injected again to 550 μmol mol^{-1}. The ventilation rate obtained using the TG technique (G_{TG}) can be determined using the following equations:

$$N_{\mathrm{TG}} = \frac{3600}{t_1}\, ln \left[\frac{C_{\mathrm{in}}(t_0) - C_{\mathrm{out}}}{C_{\mathrm{in}}(t_1) - C_{\mathrm{out}}}\right] \tag{3.2}$$

$$G_{\mathrm{TG}} = \frac{1}{60}\, \frac{N_{\mathrm{TG}}\, V_{\mathrm{g}}}{A_{\mathrm{f}}}, \tag{3.3}$$

where $C_{\mathrm{in}}(t_0)$ is the initial CO_2 concentration at $t = 0$, $C_{\mathrm{in}}(t_1)$ is the CO_2 concentration measured at $t = t_1$, V_g is the greenhouse volume (m^3), and A_f is the greenhouse floor area (m^2). A factor of 3600 is introduced because the air exchange rate (N_{TG}) is the greenhouse air exchange rate expressed the number of greenhouse volume exchanges per hour (expressed in h^{-1}) and t is measured in seconds. N_{TG} can be converted into the ventilation rate based on tracer gas, G_{TG} (m^3 m^{-2} min^{-1}) using Eq. 3.3. These measured values were used as references for comparison with the ventilation rates in the cultivation greenhouse measured using the HB and WVB methods as described below.

HB method

Ventilation removes heat from a greenhouse to prevent excessively high temperatures. The HB method assumes steady-state conditions and uses the principle of energy conservation, i.e., the heat gains are equal to the heat losses inside and outside a greenhouse. When no heating is used, the heat removed by leakage (i.e., the heat removal occurring when the vents are closed) and ventilation (Q_{v}) is equal to the solar radiation collected in the greenhouse (Q_{Rn}) minus the thermal loss through the cover (Q_{c}) and minus the stored heat in the soil (Q_{s}). Q_{s} was measured every 1 min by a soil heat flux sensor placed 10 mm below the ground surface. Mathematically, the equation for the static HB of a naturally ventilated greenhouse has the following general form:

$$Q_{\mathrm{v}} = Q_{\mathrm{Rn}} - Q_{\mathrm{s}} - Q_{\mathrm{c}} \tag{3.4}$$

$$Q_{\mathrm{c}} = k(T_{\mathrm{in}} - T_{\mathrm{out}})\frac{A_{\mathrm{c}}}{A_{\mathrm{f}}} \tag{3.5}$$

$$G_{\mathrm{HB}} = \frac{Q_{\mathrm{V}}}{\left[c_{\mathrm{p}} \cdot \rho_{\mathrm{a}} \cdot (T_{\mathrm{in}} - T_{\mathrm{out}}) + L_{\mathrm{v}} \cdot (AH_{\mathrm{in}} - AH_{\mathrm{out}})\right]} \times 60 \tag{3.6}$$

where G_{HB} is the measured ventilation rate per unit floor area over a period [m^3 m^{-2} min^{-1}]. Q_{Rn} is the average incoming net solar radiation inside a greenhouse during the day (W m^{-2}), Q_{s} is the soil heat flux (W m^{-2}), Q_{c} is the heat transfer through the greenhouse cover, Q_{v} is the heat removed via ventilation (W m^{-2}), k is the heat transmittance coefficient of the greenhouse cover (W m^{-2} K^{-1}), A_c is the covered area of the greenhouse (m^2), c_{p} is the specific heat capacity of air (J kg^{-1} K^{-1}), ρ_{a} is the specific mass of air (kg m^{-3}), T_{in}–T_{out} is the air temperature difference between inside and outside the greenhouse (K), L_{v} is the latent heat of vaporization (J kg^{-1}), and AH_{in}–AH_{out} is the absolute humidity difference between inside and outside the greenhouse (kg m^{-3}). A factor of 60 is introduced to convert the units of time from seconds into minutes.

WVB method

Water vapor was considered to originate only from crop transpiration in the growth process. The evaporation from the substrate media and greenhouse floor was neglected due to them being covered by plastic mulch. The greenhouse was assumed to be in uniformly humid and steady-state conditions. The crop evapotranspiration rate was directly measured by two weighing devices (Model SW-15KS, A&D Company, Japan) with an accuracy of 2 g. The average measured evapotranspiration was scaled up to all of plants evapotranspiration by assuming that the evapotranspiration was uniform, and adding a plant coverage factor to the total greenhouse floor area (Eq. 3.7). The plant coverage factor was measured from the real horizontal projection of the canopy, as performed by Gerson et al. (2001). The following equation was used to calculate the ventilation rate in the WVB method:

$$G_{\mathrm{WVB}} = \frac{n\ ET}{A_{\mathrm{f}}\, F_{\mathrm{ca}}\, [AH_{\mathrm{in}} - AH_{\mathrm{out}}] \times 60}, \tag{3.7}$$

where G_{WVB} is the measured ventilation rate per unit surface area of the greenhouse floor over a period of time ($\mathrm{m^3\ m^{-2}\ min^{-1}}$), n is total number of plants, ET is the measured evapotranspiration ($\mathrm{g\ h^{-1}}$), A_{f} is the greenhouse floor surface area ($\mathrm{m^2}$), F_{ca} is the ratio of the plant coverage area to the greenhouse floor area, and AH_{in}–AH_{out} ($\mathrm{g\ m^{-3}}$) is the absolute humidity difference between inside and outside the greenhouse during a certain period. The plant coverage factor was measured from the real horizontal projection of the canopy, as performed by Gerson et al. (2001).

The ventilation rate was measured using the WVB and HB methods in a naturally ventilated greenhouse cultivated with a fully grown tomato crop. The measurements were recorded every 1 min and averaged in 15 min intervals because of the time lag of the direct method used for evapotranspiration rate estimation in the WVB method. All measurements were performed on the same day, and the window aperture configuration ranged between closed (0%) and moderately open (16%). Then, all ventilation rates measured using these two methods were compared indirectly with the results of the TG method with no crops.

3.3. Results and discussion

The effects of different W on the ventilation rate were measured using the tracer gas technique (G_{TG}) without crops in a naturally ventilated greenhouse. Figure 3.2 shows the time courses corresponding to W = 0% (closed), 4% (small), and 12% (moderate), during the daytime on the measurement days (April 27 and May 2, 2019). Since the CO_2 control system could maintain the gas concentration at a predetermined level, the ventilation rate could be measured properly. The measured value of G_{TG} increased as W increased from 0% to 12%. The average G_{TG} values when W = 0%, 4%, and 12% were 0.059, 0.254, and 1.955 m^3 m^{-2} min^{-1}, respectively. Increasing ΔT increased the ventilation rate under leakage conditions, indicating that the air temperature had a greater effect on the gas flow in a greenhouse because gas volume expands with increasing temperature. However, with a small ventilation opening area (W = 4%), G_{TG} leveled off at 0.153–0.350 m^3 m^{-2} min^{-1} even though ΔT decreased linearly with decreasing solar radiation. Generally, the ventilation rate is expressed by the product of the opening area of windows, the outside wind speed, and the square root of the wind pressure coefficient. The wind pressure coefficient of a flap type window depends on the angle of its opening (Boulard and Baile, 1995). The measurement of ventilation rate with the TG method in this greenhouse correctly showed this relationship. Figure 3.2b and 3.2c showed a proportional increase in the average of G_{TG} against the window opening area from 0.254 m^3 m^{-2} min^{-1} (W=4%) to 1.955 m^3 m^{-2} min^{-1} (W=12%), and with an average wind speed outside the greenhouse of 0.3 and 0.9 m s^{-1}, respectively.

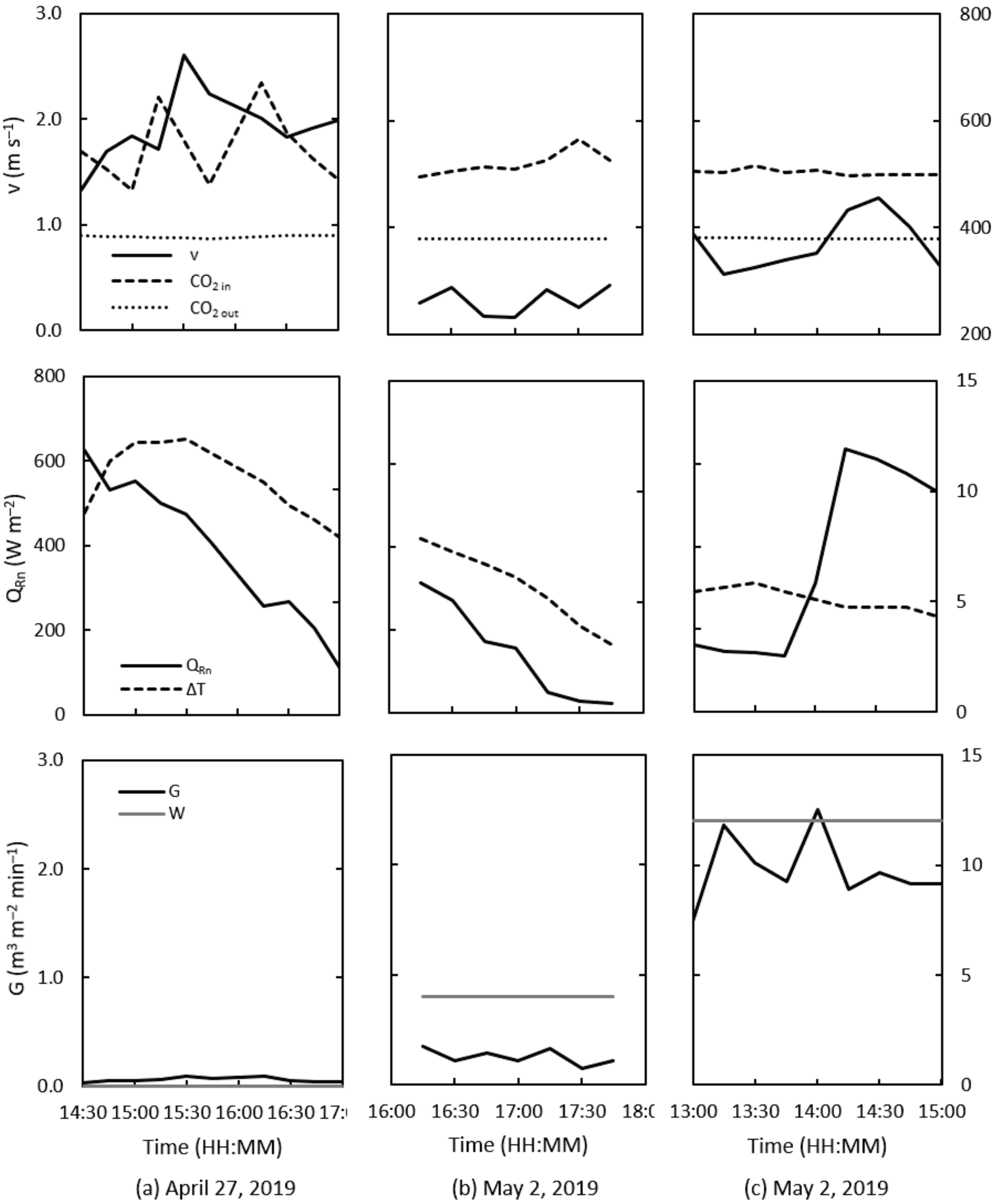
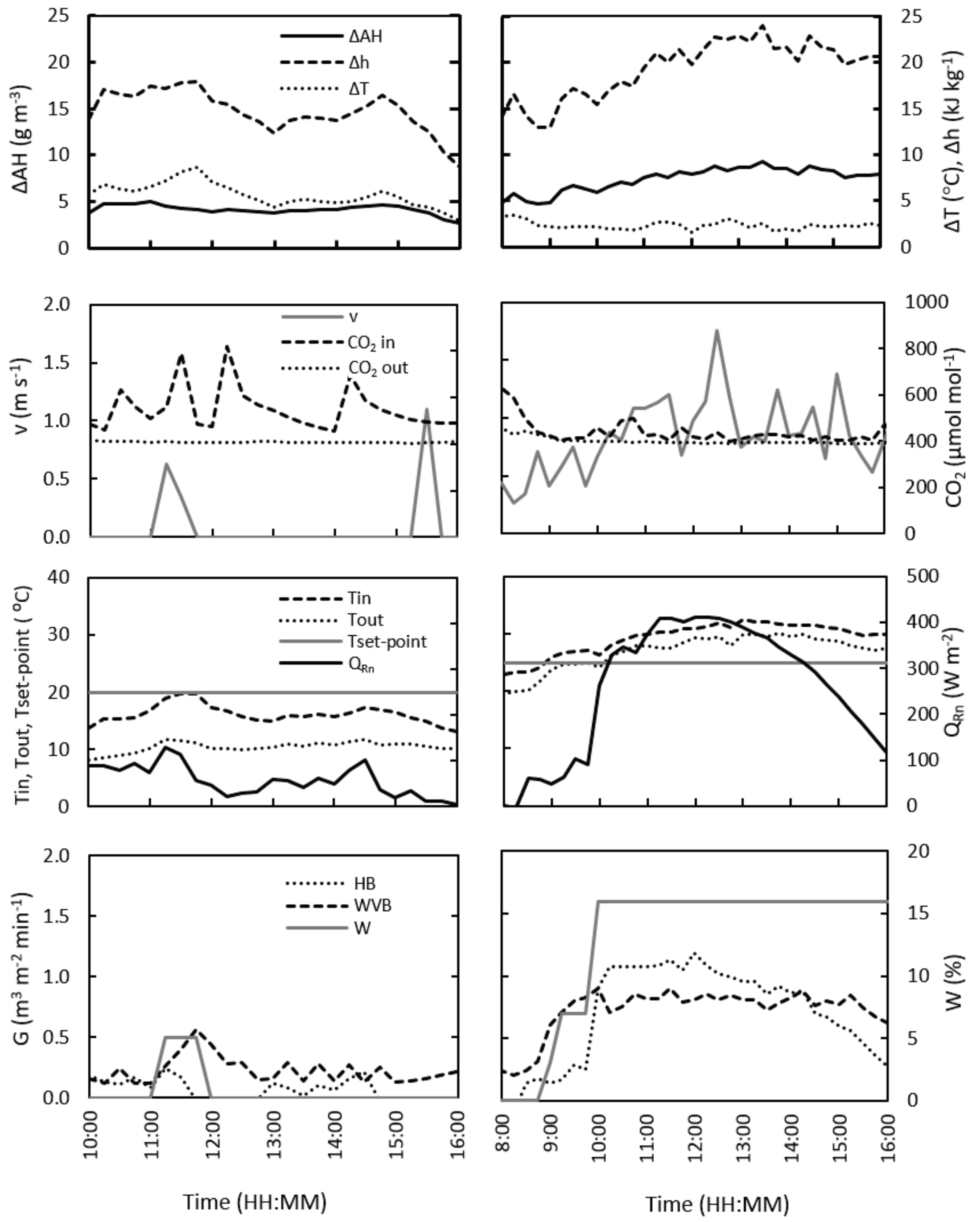


Fig. 3.2 Time series of G obtained using the TG method (G_{TG}) with no crops and small ventilation areas, as well as Q_{Rn} and v. (a) W = 0%, (b) W = 4%, and (c) W = 12%. W: ventilation opening area; Q_{Rn}: solar radiation absorbed in the greenhouse; ΔT: air temperature difference between inside and outside; v: outside wind speed; $CO_{2\ in}$ and $CO_{2\ out}$: CO_2 concentrations inside and outside the greenhouse, respectively.



(a) Dec. 14, 2019

(b) April 22, 2019

Fig. 3.3 Time series of G obtained using the HB (G_{HB}) and WVB methods (G_{WVB}) at different W in (a) winter and (b) spring. Q_{Rn}: solar radiation absorbed in the greenhouse; T_{in}, T_{out}, and $T_{set\text{-}point}$: inside air temperature, outside air temperature, and set point of temperature for ventilation; v: outside wind speed; $CO_{2\,in}$ and $CO_{2\,out}$: CO_2 concentrations inside and outside the greenhouse, respectively; ΔAH: difference in absolute humidity between inside and outside; Δh: difference in enthalpy between inside and outside; ΔT: air temperature difference between inside and outside; Tomato plants were cultivated by substrate culture in the greenhouse.

Figure 3.3 shows the time course of ventilation rate (G) obtained in winter on December 14 (Figure 3.3a) and in spring on April 22, 2019 (Figure 3.3b). CO_2 gas was supplied to maintain an inside CO_2 concentration of around 400 µmol mol^{-1} via the porous tube in center of the greenhouse in spring and between 450 µmol mol^{-1} and 550 µmol mol^{-1} in winter. During the daytime on the measurement days of December 14 and April 22, 2019, the solar radiation inside the greenhouse was less than 100 W m^{-2} and 400 W m^{-2}, respectively. Since the ventilation temperature was set at 20°C, the windows were hardly opened during low solar radiation period (December 14, 2019). With the windows closed, the values of G measured using the two methods were small. With the window opened slightly small from 11:00 to 12:00 (W = 5%), the G values measured using the WVB (G_{WVB}) method increased slightly (0.5–0.7 m^3 m^{-2} min^{-1}), while those obtained using the HB method (G_{HB}) was low (0–0.2 m^3 m^{-2} min^{-1}). Under small W conditions, the WVB method indicated a similarity in the G value to The TG method even though it was not conducted at the same time, as presented in Fig. 3.2b. However the environmental condition during measurement was almost similar, for instance: the inside net radiation (Q_{Rn}) ranged 50 – 200 W m^{-2}, temperature difference (ΔT) was 5 - 8 °C, and air velocity (v) was below 0.5 m s^{-1}.

On April 22, 2019 when the set temperature was 25 °C, the G_{WVB} showed a quick response to the rapid change in W from 9:00 to 10:00, but the G_{HB} increased with a delay of about 40 minutes (Figure 3.3b). Thereafter, both methods leveled off between 0.7 m^3 m^{-2} min^{-1} and 1.0 m^3 m^{-2} min^{-1} when W remained constant at 16%. When these results are compared with those obtained with the TG method (Fig. 3.2c) indirectly, it can be seen that the G_{TG} was twice as much as G_{HB} and G_{WVB} at W above 10%. Even the two methods were compared with the TG method in different days, but those were conducted in the same season (spring) with the greenhouse environmental condition showed a similarity in Q_{Rn}, ΔT, and v. The lower G_{HB} and G_{WVB} can be caused by the drag effect of the plants. Kacira et al. (2004) found that the greenhouse ventilation rate without crop plants was more than twice (1.54 – 3.16 $\mathrm{m^3\ m^{-2}\ min^{-1}}$) as high as that for a plant canopy zone (0.69 – 1.50 $\mathrm{m^3\ m^{-2}}$ min) when outside wind speed ranged from 0.5 to 1.0 $\mathrm{m\ s^{-1}}$ in a two-span type greenhouse with a butterfly side vents and roof vents. The present experiment agreed with the previous study with a different type of greenhouse but similar of side vent type. Moreover, the air flow pattern without the existence of plants travel along the floor of the greenhouse and left from the leeward side opening faster (Kacira et al., 2004) and the amount of CO_2 lost by ventilation was much bigger than that taken up by the plants (Nederhoff et al., 1985). It was possible to facilitate correction of the G for the presence of plants in ventilation measurement using the TG method if the amount of CO_2 absorbed by plants photosynthesis has known, but it is not recommended for practical use (Nederhoff et al., 1985). They reported that the TG method with CO_2 can be used for determining the ventilation characteristics of greenhouse when it is free of plants.

Furthermore, the G_{HB} performed in a similar manner to the G_{WVB} with increased net radiation and W. At the same window opening, G_{HB} decreased as the decline in solar radiation, while that obtained using the WVB method did not change. This result indicated that the G_{HB} was mainly affected by solar radiation. The microclimate difference in the greenhouse and the outside wind speed also contributed to the change in ventilation rate. It was clear that the accuracy of the HB method depends on the position of the solar radiation sensor in the greenhouse. A shadow of direct radiation on the sensor cannot be neglected if the HB method is based on this sensor. Akutsu et al. (2015) noted that using double sensors or a diffused covering material would help solve this problem. However, it was not easy to evaluate the difference between double sensors because of the constraints in selecting method of the value to be used. Moreover, they explained that the use of two sensors could solve the shadow problem, but it has not been completely resolved because matching the two outputs should be more improved. Takakura (2008) proposed a plant solar meter with a spherical sensor for HB that should be used to measure the solar radiation at the top of the canopy to minimize this problem and enable more effective greenhouse environmental control. Therefore, the measurements in this experiment were performed with one radiation sensor above the canopy.

Table 3.1 Performance of the HB and WVB methods under different window apertures in spring and winter season.

Ventilation step	W (%)	n data	Climate Condition* Q_{Rn} W m^{-2}	v m s^{-1}	ΔT °C	VPD kPa	Ventilation rate (m^3 m^{-2} min^{-1})** WVB	HB	Air exchange rate (h^{-1})** WVB	HB
SV2-RV1	Spring (April 20–22, 2019)									
S0	0	13	29	0.4	3.1	0.2	0.173 ± 0.009	-0.112 ± 0.036	4.6 ± 0.2	-3.0 ± 1.0
S1	3	5	62	0.4	4.6	0.4	0.260 ± 0.031	0.094 ± 0.125	6.9 ± 0.8	3.3 ± 2.5
S2	7	3	85	0.6	2.2	2.4	0.777 ± 0.036	0.232 ± 0.034	20.7 ± 1.0	6.2 ± 0.9
S3	12	12	186	1.5	3.9	0.5	0.582 ± 0.036	0.439 ± 0.078	15.5 ± 1.0	11.7 ± 2.1
S4	16	27	353	1.0	2.2	3.5	0.810 ± 0.017	0.819 ± 0.059	21.6 ± 0.4	21.8 ± 1.6
SV0-RV1	Winter (December 12–19, 2019)									
S0	0	81	52	0.1	5.6	0.2	0.167 ± 0.010	0.031 ± 0.015	4.5 ± 0.3	0.8 ± 0.4
S1	2	7	110	0.3	7.4	0.1	0.177 ± 0.009	0.073 ± 0.058	4.7 ± 0.2	2.0 ± 1.5
S2	4	22	138	0.5	8.3	0.2	0.230 ± 0.029	0.126 ± 0.031	6.1 ± 0.8	3.4 ± 0.8
S3	6	25	194	0.7	8.8	0.3	0.235 ± 0.031	0.229 ± 0.038	6.3 ± 0.8	6.1 ± 1.0
S4	13	5	281	0.3	7.7	1.3	0.949 ± 0.065	0.899 ± 0.158	25.3 ± 1.7	24.0 ± 4.2

*Means of climate data conditions for *n* data. *W*: window aperture, Q_{Rn}: inside net radiation, *v*: outside wind speed, ΔT: temperature difference between inside and outside, and *VPD*: vapor pressure deficit.
**The means and standard errors are shown in the ventilation and air exchange rate values.

On the other hand, *G* is affected by the difference between the absolute humidity inside and outside (ΔAH) (Figure 3.3), as well as by the vapor pressure deficit (*VPD*; Table 3.1). The WVB method was affected by the measurement accuracy of the evapotranspiration in the greenhouse. Most of the water vapor is generated by plants in soilless culture greenhouses in which the floor surface was covered by mulch. Plant transpiration is related to the LAI, solar radiation, *ΔAH* (Jolliet and Bailey 1992; Katsoulas et al. 2001), and wind speed (Jolliet and Bailey 1992; Thongbai et al. 2010). The measurement of the direct transpiration rate by the gravimetric method was simpler than the measurement of many environmental parameters by using the HB method. However, it should be performed under an optimal range of VPD values in a greenhouse. Shamsiri et al. (2018) reviewed that the optimal VPD values were in the range of 0.3 to 1.0 kPa for tomato crop transpiration in several references.

Table 3.1 presents the overall performances of the HB and WVB ventilation rate measurement methods. The ventilation rate increased as W changed from 0% to 16% (spring) and to 13% (winter). The HB method had problems in predicting G when W was 10% or lower (S0 - S2 and S0 – S3 in spring and winter, respectively). When ventilation windows were closed, the G_{HB} was -0.112 and 0.031 $m^3 m^{-2} min^{-1}$ under low radiation condition (ranged 29 – 52 W m^{-2}). These values were lower than the G_{WVB} of 0.173 and 0.167 $m^3 m^{-2} min^{-1}$ in spring and winter seasons, respectively. Likewise, when the ventilation opening area was small (S1, 5 – 7% of W), It showed that the G_{HB} was lower than G_{WVB} with radiation ranged from 62 to 110 W m^{-2}. The G value predicted using the HB method was lower than that obtained using the WVB method under leakage conditions and the smallest ventilator area due to the lowest net radiation level (below 200 W m^{-2}). However, the G value acquired using the HB method increased when the ventilator level was more than 10%, which will be achieved at high radiation levels. With high solar radiation and a moderate value of W (13% and 16%) as presented in Table 3.1, the HB method agreed well with the WVB method.

In term of the HB problem at lower radiation during experiments, this tendency was also experienced in other experiments, as reported by Fernandez and Bailey (1992) and Yasutake et al. (2017). It is unclear, however, why this occurs and when this method can be used to predict the ventilation rates properly. We attempted to elucidate the source of this problem by performing HB model evaluation using the percentage of the net radiation collected in the greenhouse, as presented in Fig. 3.4. This graph depicts the ratio of each HB item to the absorbed solar radiation in a single-span type greenhouse under different window apertures. In Figure 3.4, three main energy parameters influence the HB ventilation rate prediction performance: thermal loss through the cover (Q'_{cv}), heat storage in the soil (Q'_{st}), and energy lost by ventilation (Q'_{v}). All energy was absorbed from the net radiation inside the greenhouse (*Rn*).

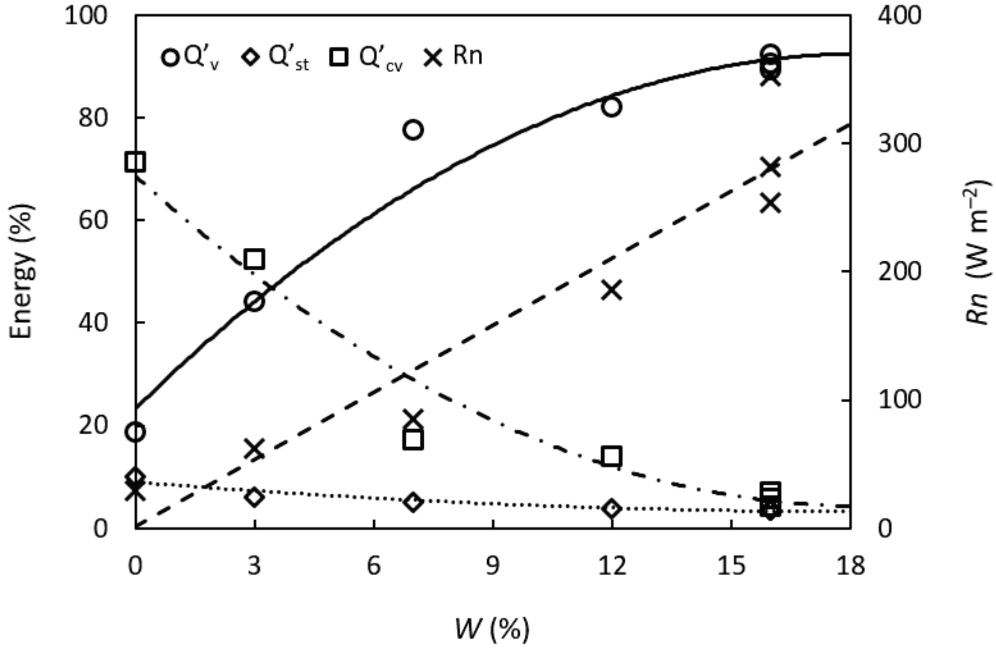


Fig. 3.4 Evaluation of the HB model expressed as a percentage of the net radiation collected in the single-span experimental greenhouse under different window apertures on April 20–22, 2019. Q'_{v} is the energy ratio removed from the greenhouse by the leakage processes and ventilation, Q'_{st} is the energy ratio stored in the soil of the greenhouse floor, Q'_{cv} is the energy ratio from the thermal loss through the cover, and Rn is the net solar radiation inside the greenhouse.

Figure 3.4 shows that Q'_{v} in the greenhouse increased in response to increasing W, corresponding to an increase in Rn. On the contrary, Q'_{st} decreased slightly and tends to be flat in response to increasing W. Q'_{cv} decreased dramatically with increasing W. When $W = 0\%$, the sum of Q'_{cv} and Q'_{st} is 81%, while Q'_{v} is only 19%. Consequently, the ventilation rate predicted using the HB method was lower than those obtained using the other methods (Figure 3.2 and Table 3.1). Furthermore, when ventilation begins with $W = 3\%$, Q'_{v} increased twice, reaching over 40%. However, the increase in Q'_{v} was not enough to predict the ventilation rate properly because the total of Q'_{cv} and Q'_{st} was still greater than Q'_{v}. Consequently, the response of the HB measurements was slow in the morning, even though W began to increase with increasing Rn. This observation indicated that the energy entering the greenhouse in the morning had heated the entire greenhouse material structure and greenhouse floor area. The HB method started to exhibit G values equal to those of the other methods when $W = 13\%–16\%$, as presented in Figure 3 and Table 3.1. Figure 3.4 demonstrated that Q'_{v} was greater than the total energy from Q'_{cv} and Q'_{st}, reaching over 80% when the net radiation level was above 200 W m^{-2}. Thus, the HB method produced better ventilation rates when the ventilation opening area was moderate to high. This condition often occurs during late spring, summer, and early autumn, when the radiation level is high. Fernandez and Bailey (1992) and Baptista et al. (2001) reported that the HB achieved excellent performance in high ventilation situations.

3.4. Conclusion

In conclusion, the HB and WVB methods of ventilation rate measurement were compared directly and simultaneously in spring and winter. The indirect comparison was that of the HB or WVB method with the TG method. The HB method achieved in similar ventilation rate with the WVB method at moderate *W* (13%–16%) with inside solar radiation of more than 200 W m^{-2}. The WVB method produced *G* values similar to those of the TG method at small *W* and performed similarly to the HB method at moderate *W* under optimal VPD conditions in a greenhouse. However, the WVB approach yielded slightly higher ventilation rates under leakage conditions due to the lowest VPD. Since it is time consuming to monitor the photosynthetic rate of whole plants in a greenhouse to evaluate the yield of cultivated plants, the WVB approach may permit in real-time and continuous greenhouse ventilation rate measurement because it is more straightforward than the HB and TG methods at small and moderate *W*. This present work could facilitate the achievement of real-time continuous monitoring of greenhouse ventilation rates, as is needed for photosynthetic rate estimation. Future studies involving higher ventilation supported with optimum VPD, such as in summer and early autumn, must also be conducted. In addition, further larger-scale (all of the cultivated plants or canopy) reviews are essential.

CHAPTER 4 Photosynthetic rate monitoring via water vapor balance and CO_2 balance method in naturally ventilated greenhouse

Abstract

Recent studies propose the combination method of water vapor balance and CO_2 balance in the greenhouse to predict tomato crop photosynthetic rate continuously. The greenhouse cultivated mature tomato plants was supplied with CO_2 to maintain inside CO_2 concentration at the same level with ambient level concentration. Predicted photosynthesis value was measured using water vapor balance techniques based on leaf area index (WVB-LAI) and population basis (WVB-POP) for estimating the ventilation rate value (G) that used for CO_2 balance method. The predicted value was compared and validated with the direct measurement of photosynthesis using a portable infrared gas analyzer with leaf chamber LI-6400XT (Control). For real-time monitoring, the sap flow sensor that measured the transpiration rate (Tr) as primary sources of the WVB method was conducted and calibrated with an electronic weighing balance with r=0.89. The G value performed at maximum window aperture in late spring and summer 2019, and the $G_{\text{WVB-POP}}$ and $G_{\text{WVB-LAI}}$ correlated significantly with the heat balance method (G_{HB}) with r=0.91 and 0.89, respectively. The photosynthesis (Pn), Tr, and leaf temperature of tomato crops were affected by photosynthetic photon flux densities (PPFD). The transpiration rate had a positive correlation with photosynthesis. The estimated Pn using the proposed WVB-POP and WVB-LAI techniques had a high accuracy in sunny and cloudy day. The results indicated that the proposed method could be applied to a commercial greenhouse for estimating the Pn. Also, the process allows estimate Pn continuously for monitoring plant growth in a greenhouse.

4.1. Introduction

The monitoring of the canopy photosynthetic rate has become necessary to estimate plant growth and CO_2 efficiency in a greenhouse. The method of measuring canopy photosynthesis involved an accurate estimation of the greenhouse CO_2 balance (Nederhoff and Vegter, 1994). The photosynthetic rate can be predicted using CO_2 balance if the ventilation rate or air exchange rate value is known. Hence, the air exchange rate is significant not only for estimating the net photosynthesis but also affecting the development and production of the crop in the greenhouse.

Several studies have shown that the air exchange rate value can be predicted using tracer gas method (Boulard and Draoui, 1995; Papadakis et al., 1996; F.J. Baptista et al., 1999), heat balance method (Fernandez and Bailey, 1992; Demrati et al., 2001; Harmanto, Tantau and Salokhe, 2006a), and water vapor balance method (Harmanto, Tantau, and Salokhe 2006a; Boulard and Draoui 1995). The tracer gas and the heat balance method is the most widely used (Fernandez and Bailey, 1992). The findings of the tracer gas technique gave greater accuracy of the air exchange rate measurement at leakage and smallest window aperture (Nederhoff, van de Vooren and ten Cate, 1985; Fernandez and Bailey, 1992; F.J. Baptista et al., 1999; Muñoz et al., 1999). In contrast, other studies have shown that the energy balance method has good accuracy at larger ventilator openings (Fernandez and Bailey, 1992; Baptista, Bailey and Meneses, 2001).

However, the two-type measurement of the ventilation rate has several difficulties in a practical view. The tracer gas technique requires the most equipment as well as sophisticated control systems and real-time data acquisition (Sherman, 1990). Also, the tracer gas methods presented numerous disadvantages under large-scales greenhouse

(Demrati et al., 2001) whereas the mixing problem presented a primary potential source of error; and also, this techniques may not allow the determination of the real airflow but characterize the effective airflow (Boulard *et al.*, 1996; Nikolopoulos et al., 2012). While, the difficulty in using the energy balance technique is the need to measure a large number of variables, and a single inaccuracy can have a significant effect on the final results of ventilation rate value (F.J. Baptista et al., 1999). Also, it was not possible to use the heat balance method when radiation was low due to typically high errors (Yasutake et al., 2017). Therefore, we need an alternative approach that can predict ventilation rate on different radiation levels and window apertures.

There is another alternative method, namely the water vapor balance method. It has better accuracy and good agreement with other measurement techniques under a small ventilator opening area (Boulard and Draoui, 1995; Harmanto, Tantau and Salokhe, 2006b) and in a greenhouse cultivated with mature plants (Harmanto, Tantau and Salokhe, 2006b). Also, the method had been applied in various type of greenhouse with a good result, for instance: multi-spans greenhouse type with continuous roof vents only (Boulard and Draoui, 1995; Kittas et al., 2002) and with constant roof and side vents configuration (Mashonjowa et al., 2010), screen house type (Harmanto, Tantau, and Salokhe, 2006b; Rigakis et al., 2015), and growth chamber (Li et al., 2012). However, there are some challenges of water vapor balance method, i.e., errors value measurements due to direct solar radiation penetration and temporary shading to the lysimetric device (Kittas et al., 2002); overestimation of ventilation rate in the night time (Mashonjowa et al., 2010); error of scaling-up crops transpiration from a single plant (or a few plants) to whole canopy transpiration (Boulard and Draoui, 1995; Mashonjowa et al., 2010). While Li et al. (2012) reported that the water vapor balance could be used to estimate photosynthesis in high accuracy under growth chamber experiments, but it remains an open question whether this technique can predict and monitor the ventilation rate and the net photosynthesis values accurately in a greenhouse because the previous research has been not tested and validated yet with direct measurement of photosynthetic rate under the greenhouse with a high level of the window aperture.

This paper proposed the modification of water vapor balance method based on the number of the plant in a greenhouse by added a parameter value ratio of canopy factor area to greenhouse floor area; and then, compared with the technique has been used by Ham et al., (1990) and Mashonjowa et al., (2010). Also, we tested whether the proposed method would predict the ventilation rate and the net photosynthetic rate inside the naturally ventilated greenhouse accurately compared with the measured photosynthetic rate using a portable infrared gas analyzer with a leaf chamber system.

4.2. Materials and methods

Greenhouse and plant experiments

The experiment was performed in two single-span naturally ventilated greenhouses at a research field site of the Faculty of Applied Biological Science, Gifu University, Japan. The two greenhouses were covered using plastic material with dimensions of 5 m × 10 m × 3 m (Figure 4.1a). 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 (0.8 mm with porosity 62%, in the greenhouse with CO_2 fertilizer). The experiment was performed under a large opening area of ventilator condition presented with *W* value in percentage. The *W* value was calculated based on the ratio of the total ventilation area to the greenhouse floor area (Eq. 4.1).

$$W = \frac{Total\, window\, opening\, area\, (m^2)}{Greenhouse\, floor\, area\, (m^2)}\, x\, 100\% \tag{4.1}$$

The greenhouse was occupied by mature tomato crops (*Lycopersicon esculentum* Mill., variety 'Momotaro'), cultivated on the two-bed system using substrate cultivation 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 growing medium in bed systems was covered with plastic mulch. During the measurement periods in spring and summer seasons 2019, the tomato crop had an average height of about 1.5 m, and the leaf area index of the crop was about 3.8. 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 following climatic data were recorded: greenhouse air temperature both inside and outside (dry and wet bulb temperature), leaf temperature, net radiometer (CNR2, Kipp and Zonen, The Netherlands), and outside total solar radiation, and outside wind velocity. The air temperature (dry and wet bulb temperature) was measured by two aspirated psychrometers using T-type thermocouple (copper/constantan) sensors. Two psychrometers were set up at a different height of 0.3, 1.2, 1.8, and 2.2 m above the floor in the center of the greenhouse. The leaf temperature was measured using an infrared thermometer (Model IT-480, HORIBA, Japan) with a maximum distance of 1.0 m between the tomato crop canopy and the sensor. All the above measurements were recorded in the CADAC3 data logger (ETO Denki, Japan) every minute. Then, the predicted ventilation rate value was averaged in 5 minutes interval from 11:00 AM to 2:00 PM.

Water vapor balance technique

For computing the ventilation rate in the greenhouse using the water vapor balance technique, the water vapor inside (AH_{in}) and outside (AH_{out}) air the greenhouse were measured as absolute humidity in (g m^{-3}) from dry and wet temperature measurement data. Greenhouse crops transpiration rate (g h^{-1}) of tomato crops was measured by an indirect method using the sap flow gauges (Model SGA13-WS, Dynamax Inc., USA) attached to the stem of the tomato plant (Figure 4.1c). For minimizing the errors from the transpiration rate sensor, it was calibrated with the direct method measurement by a weighing device (Model SW-15KS, A&D Company, Japan) with an accuracy of 2 g. This calibration was evaluated on the same plant that cultivated with the pot system. Transpiration rate was measured and recorded every minute and then averaged 15-minutes intervals during the daytime.

We assumed that the greenhouse was uniformly humid and in a steady-state condition. All the above measurements were recorded in a data logger (CR1000, Science Campbell, USA). The transpiration rate from the sap flow sensor was scaled up to whole tomato crop transpiration by assuming that evapotranspiration was uniform throughout the crops using two different equations. First, the ventilation rate was predicted by the equation, as mention by (Ham, Heilman, and Lascano, 1990; Mashonjowa et al., 2010) based on leaf area index (Eq. 4.2). Second, we proposed the transpiration rates on both methods were measured on the same plant and then converted to a unit land area basis by normalizing the stem flow and weighing device data with an added variable fraction of the total greenhouse floor area covered by the crop on a population basis (Eq. 4.3).

Fig. 4.1 (a) Naturally ventilated experimental greenhouse with CO_2 fertilizer (left) and without CO_2 supply (right); (b) photosynthesis measurement using a portable leaf chamber system (LI-6400, Licor, USA); (c) DynagaugeTM Sap Flow sensor installed on tomato stem that covered with the velcro strap, foam bodies, the white waterproof, and the bubble shield to prevent direct sunlight to sensor.

$$G_{WVB-LAI} = \frac{Tr\ LAI}{L_A\ [AH_{in} - AH_{out}] \times 60}, \qquad (4.2)$$

$$G_{WVB-POP} = \frac{n\,Tr}{A_{f}.\,F_{ca}\cdot[AH_{in} - AH_{out}] \times 60}, \qquad (4.3)$$

Where $G_{WVB\text{-}LAI}$ and $G_{WVB\text{-}Pop}$ [m^3 m^{-2} min^{-1}] are the measured ventilation rates per unit greenhouse surface floor area over a period of time for evapotranspiration based on leaf area index and population, respectively; T_r is transpiration rate of tomato plant [g h^{-1}]; n is the total number of plants; A_f is the greenhouse surface floor area [m^2]; F_{ca} is the fraction of the total greenhouse floor area covered by the crop (0.2 - 0.4); and AH_{in}–AH_{out} [g m^{-3}] is the absolute humidity difference between the inside and outside of the greenhouse over a period of time.

Measurement of the net photosynthetic rate (Pn)

After the ventilation rate value using water vapor balance technique was estimated with two-type measurement methods (WVB-POP and WVB-LAI). The prediction of ventilation rate value using the water vapor balance technique was used for determining the net photosynthetic rate based on the CO_2 balance technique (Eq. 4.6). The CO_2 balance in the greenhouse is given by:

$$\frac{V_g}{A_f}\frac{dC_{in}}{dt} = R + S + G\,(C_{out} - C_{in}) - P_n \qquad (4.4)$$

$$P_n = R + S + G\,(C_{out} - C_{in}) - \frac{V_g}{A_f}\frac{dC_{in}}{dt} \qquad (4.5)$$

Where G is the ventilation rate estimated using water vapor balance technique (m^3 m^{-2} min^{-1}); S is the CO_2 supply rate (m^3 CO_2 m^{-2} min^{-1}); P_n is CO_2 exchange rate of plants (m^3 CO_2 m^{-2} min^{-1}); R is soil respiration rate (m^3 CO_2 m^{-2} min^{-1}). Assumed that the R value was neglected due to cultivation using soilless culture, and floor greenhouse was covered by plastic. Hence, the predicted photosynthetic rate can be computed by the following simple equation:

$$P_n = S + G\ (C_{out} - C_{in}) - \frac{V_g}{A_f}\frac{dC_{in}}{dt} \qquad (4.6)$$

There was two treatments greenhouse for evaluating the photosynthetic rate of tomato crops, i.e., greenhouse with CO_2 supply to maintain CO_2 concentration in the inside greenhouse at an ambient level, and without CO2 supply. A level of average ambient concentration (CO_2 in = CO_2 out, c.a. 380 ppm) was maintained during observations. A level of ambient concentration level was maintained to prevent CO_2 depletion of the greenhouse atmosphere. Hence, the CO_2 fertilizer was supplied by gas injection of porous tubes in two beds in the greenhouse using the CO_2 fertilizing controller device (C.H.C. System Co., Japan). The supply rate of CO_2 in the greenhouse was measured using a mass flow meter Model 8550 series (KOFLOC, Japan). All data were recorded in CADAC3 (ETO Denki, Japan) every second, and then averaged every minute and 5 min interval.

Monitoring of photosynthetic rate using a combination of water vapor balance and CO_2 balance technique was compared and validated with measured photosynthetic rate by using a portable leaf chamber system LI-6400XT (Control), as presented in Figure 4.1b, (LI-COR Inc., USA) in the mid-day (between 1100 – 1400) on both clear and cloudy days in late spring and early summer seasons (May 16th, 23rd, 29th, 31st, and June 4th – 5th, 2019). The measurement of gas exchange characteristics was carried out on mature and fully expanded leaves of tomato plants that supported with CO_2 supply in the greenhouse. Measurements were taken on six plants of tomato plant at fifth leaf truss (counted from the top). In measurements, data recorded every 10 s for 5 min at constant PPFD.

Data analysis

Statistical analysis of ventilation rate value characteristics (G) and photosynthetic rate under a high level of window apertures condition and application of CO_2 fertilizer were conducted using Tukey-Kramer's test, with significance defined as P=0.05 by using statistical formula in Ms. Excel.

4.3. Results and discussion

Sap flow performance for water vapor balance method

For monitoring in a real-time condition of ventilation rate using a water vapor balance technique, the sap flow sensor was calibrated using the weighing device. Results showed that measurement of tomato crops transpiration with a sap flow sensor (indirect method) has a high correlation with the control, a weighing device (direct method), and the corresponding value of the Pearson correlation coefficients (r) was 0.89. Figure 4.2 illustrates the value of the transpiration rate (Tr) with the weighing device was slightly higher than the sap flow sensor. It can be explained due to the addition of water vapor from the substrate evaporation even it was covered by plastic mulch. However, the value of evaporation from growing media was too small by 6.3% from the total of evapotranspiration only.

Based on the result, it can be directly used the transpiration rate value from the sap flow sensor for further investigating and monitoring of the ventilation rate using the water vapor balance technique. Practically, we should calibrate and regularly check the sap flow sensor every two weeks to make sure the accuracy of transpiration data. Also, change the position of the sensor on stem plants to other plants.

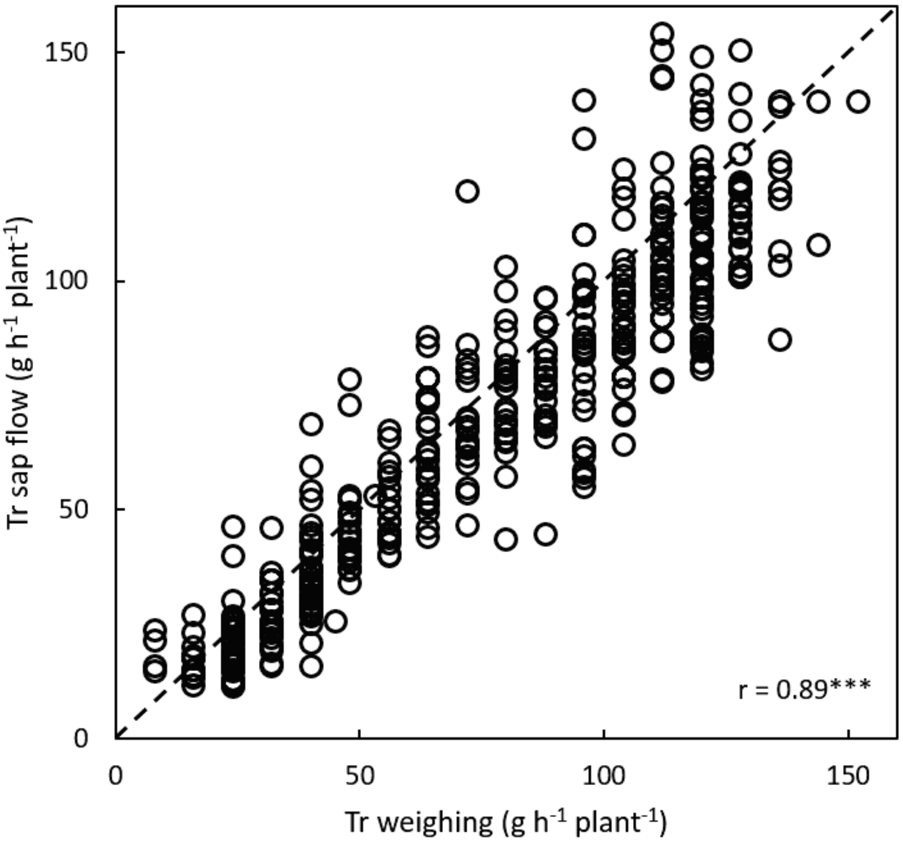


Fig. 4.2 Relationship between the transpiration rates of tomato crops obtained using the weighing device and the sap flow measurement (o) with pot systems from February until April 2019 (404 observations). The dashed line indicates the targeted line, and the corresponding value of the Pearson correlation coefficient (r) is presented in the figure (*** $p = 2.2 \times 10^{-16}$).

Greenhouse ventilation rate using water vapor balance method

The performance of water vapor balance to estimate ventilation rate value was validated with the heat balance method. Fernandez and Bailey (1992) reported that the energy balance method gives better results for higher ventilator aperture or high level of vents opening. It is a reason why the water vapor balance method was compared with the heat balance method due to under high level of window aperture conditions like in late spring and summer season.

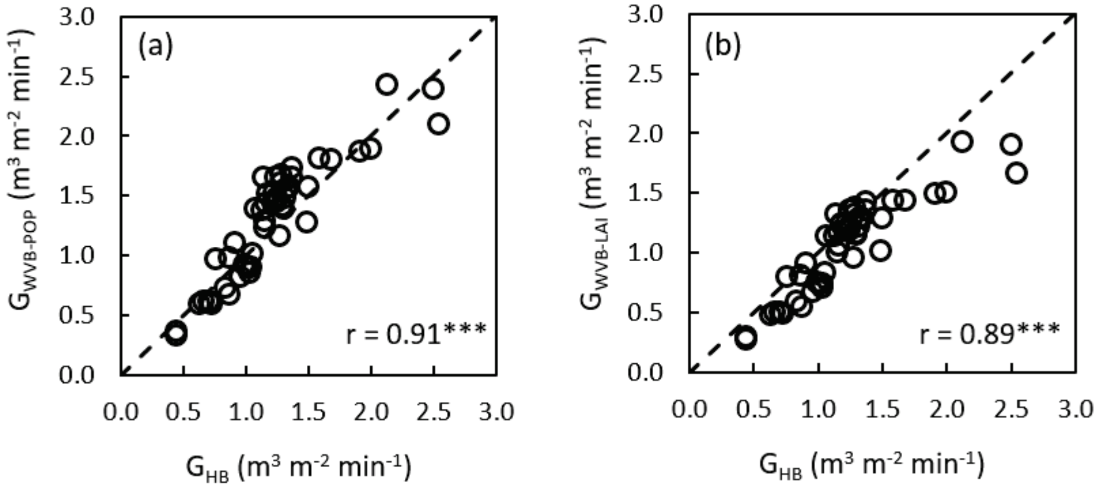


Fig. 4.3 Relationship between ventilation rate (G) using water vapor balance method (WVB) and the heat balance method (HB). (a) Correlation of G_{HB} and $G_{WVB-POP}$ with the corresponding value of the Pearson correlation coefficient (r) is presented in the figure (***p=2.2 × 10^{-16}); and (b) Correlation of G_{HB} and $G_{WVB-LAI}$ with r=0.89 (***p=2.2 × 10^{-16}). Observations were conducted on April 16 and 26, 2019 (51 observations)

Figure 4.3 figures out the relationship between the ventilation rates estimated using the water vapor balance method and the heat balance method. The ventilation rate with the water vapor balance method calculated based on the number of tomato crops ($G_{WVB-POP}$) and leaf area index ($G_{WVB-LAI}$) compared to the heat balance method (G_{HB}). During an observation on April 16th and 26th, 2019, with average inside net radiation in the greenhouse was 484 W m^{-2} (141 – 621 W m^{-2}), and the evapotranspiration rate from tomato plant was 115 g h^{-1} per plant. The window apertures condition (W) opened from 10% until 45% with average outside wind speed was 1.0 m s^{-1} (0.1 – 2.9 m s^{-1}). As shown in Fig. 3, the $G_{WVB-POP}$ and $G_{WVB-LAI}$ correlated significantly with the G_{HB} (r = 0.91, p = 2.2 x 10^{-16}; and r= 0.89, p = 2.2 x 10^{-16}, respectively).

The result indicated that G value could be estimated using water vapor balance technique under moderate until the top level of window aperture condition. The predicted value using $G_{WVB-POP}$ is a simple method and has a better result than $G_{WVB-LAI}$. In contrast, the $G_{WVB-LAI}$ is more complicated because it needs to consider the plant growth factor (leaf area, leaf area index, plant canopy covering). Overall, both methods may be allowed to conduct for monitoring the ventilation rate in the greenhouse.

Direct photosynthesis measurement

The photosynthetic rate measurement was carried out on several variations of photosynthetic photon flux density (PPFD) in the greenhouse. The relationship graph of light intensity to photosynthesis can be used as a reference to validate the findings of predicted photosynthetic rate and to monitor the rate of photosynthesis with a combination of the CO_2 balance method and the water vapor balance method.

Figure 4.4 shows rates of net photosynthesis (P_n), transpiration (T_r), and leaf temperature (TL) of tomato leaves were affected by photosynthetic photon flux densities (PPFD) of 300 – 1300 μmol m^{-2} s^{-1}. P_n gradually elevated with the increase of PPFD from 300 to 1300 μmol m^{-2} s^{-1}. Maximum Pn was 24.4 μmol m^{-2} s^{-1} at 1300 μmol m^{-2} s^{-1} PPFD. In terms of T_r and TL, PPFD had a strong correlation with leaf temperature and transpiration rate. Both TL and T_r linearly increased from 300 to 1300 μmol m^{-2} s^{-1}. TL and T_r were highly correlated. The optimum TL for maximum P_n was 30 ^{O}C after that, P_n declined significantly. The transpiration rate correlated positively with photosynthetic rate.

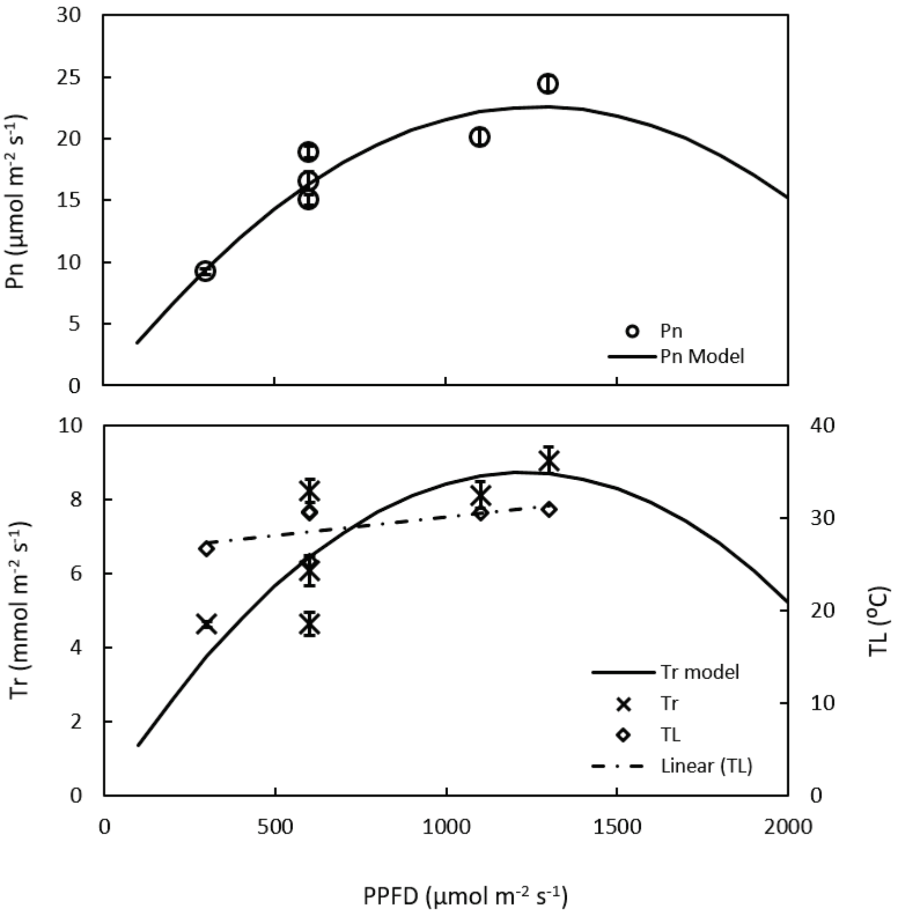
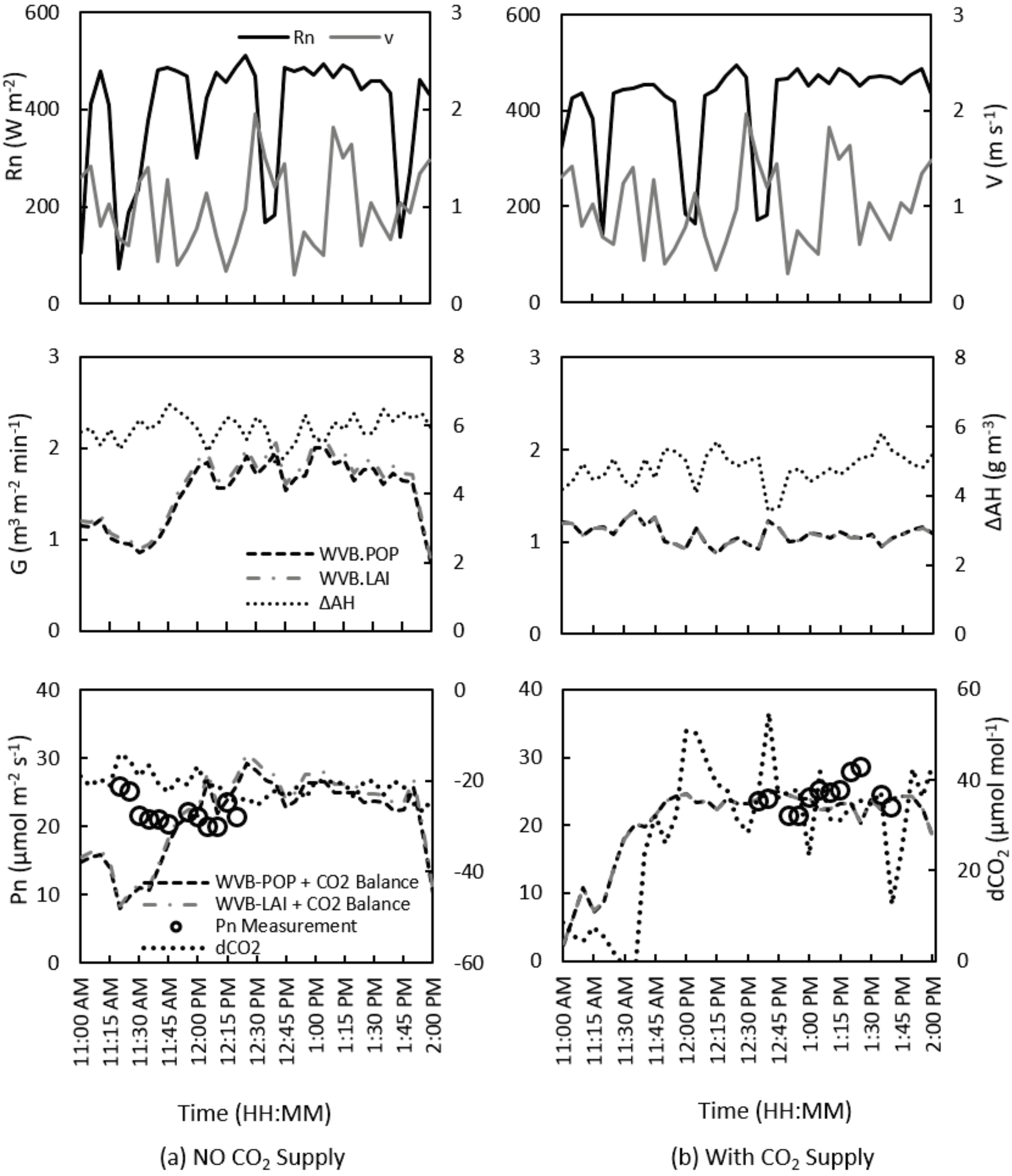


Fig. 4.4 (a) Measured net photosynthetic rate (o) using a portable leaf gas exchange (LI6400, LICOR) with CO_2 fertilizer (CO_2 in=CO_2 out) under different of PPFD value. The photosynthetic rate model presented in Pn = -1.4 × 10-5 × $PPFD^2$ + 0.035 × PPFD with R^2=0.88. (b) the tomato crop transpiration rate (x) and canopy leaf temperature, TL (◊) under different of PPFD and the transpiration rate model presented in Tr = -5.8 × 10-6 × PPFD2 + 0.014 × PPFD with R^2=0.58. Observations were conducted during mid-day (1100 – 1400) on May 16, 23, 24, 29, and June 4-5, 2019, with air temperature and humidity inside greenhouse were 25-30 ^{O}C and 40-65%, respectively. The means and standard errors of 6 datasheets are shown.



(a) NO CO_2 Supply

(b) With CO_2 Supply

Fig. 4.5 Photosynthetic rate monitoring using water vapor balance technique (based on population, WVB-POP; and Leaf area index, WVB-LAI) and direct measurement using LICOR (Pn Measurement) in a greenhouse with (a) No CO_2 Supply, (b) with CO_2 supply to maintain CO_2 concentration at an ambient level on May 16, 2019. During the observation, the window opened at maximum opening conditions.

Photosynthesis and transpiration were limited by high levels of solar radiation, like in late spring and summer. As radiation increases the greenhouse air temperature and thus promotes the automatic ventilation. At this condition resulted in reducing transpiration due to stress conditions on plant and stomata will be close (Marcelis, 1989), hence the value of the rate of transpiration and photosynthesis will decrease, as presented on model in Figure 4.4. On the contrary, in the winter season, Tartachnyk and Blanke (2007) stated that photosynthesis and transpiration were primarily limited by light but neither by stomatal conductivity nor by CO_2 concentration. Moreover, the performance of the window aperture is crucial in naturally ventilated conditions to maintain an excellent micro-climate inside the greenhouse. It is reflected by the value of the ventilation rate, where the value increases with increasing window openings (Figure 4.3). Also, the value of the ventilation rate is an essential parameter to estimate the photosynthetic rate using the CO_2 balance method.

Monitoring of photosynthetic rate using water vapor balance

Figure 4.5 shows the measurement and prediction of photosynthetic rate in the greenhouse with and without CO_2 supply on May 16, 2019. During photosynthesis rate monitoring both in tomato crops greenhouse, it was strongly relevant between the net radiation inside the greenhouse with photosynthetic rate. During the observation, it was a sunny day with the average of net radiation was 427 W m^{-2}, and the PAR value was 1300 μmol m^{-2} s^{-1}. On a sunny day, the tomato crop photosynthesis was around 24.4 μmol m^{-2} s^{-1} and 21.8 μmol m^{-2} $s^{-}1$, in the greenhouse with CO_2 supply and without CO_2 supply, respectively. On the contrary, there was a decreasing in photosynthetic rate (9.2 μmol m^{-}

^{2} s^{-}1, with CO_2 supply) at cloudy day (Rn=185 W m^{-2} or PAR=300 µmol m^{-2} s^{-}1), as presented in Table 4.1.

CO_2 supply via tube around of tomato bed can maintain the local zone of carbon dioxide around the crop equal with the ambient level. The CO_2 difference between inside and outside (dCO_2) fluctuated around 0 – 35 µmol mol^{-1}. The effect of the light intensity and the CO_2 concentration is obvious. A peak in photosynthesis can be explained by a peak in radiation or light intensity around 1.15 PM with a value of 24.4 µmol m^{-2} s^{-1}, as presented in Figure 4.5b. Between 11:00 AM and 11:45 AM, photosynthesis was lower than 20 µmol m^{-2} s^{-1} due to the low radiation and the difference of CO_2 inside and outside the greenhouse. After that, the photosynthesis value was stable and had the same value as the measured value by LICOR due to stable of light intensity.

However, in the greenhouse without CO_2 supply suffered the CO_2 depression of 20 – 26 ppm (Fig. 4.5a), even the ventilation condition was open largely. The monitoring of the predicted photosynthetic rate was lower than measured between 11:15 and 11:45 due to the lower ventilation rate value (G). It was affected by low radiation (below 200 W m^{-2}) and outside wind speed (below 1 m s^{-1}) during that time that influenced the absolute humidity value inside greenhouse even the vents open maximum condition. After that, an increase in ventilation rate (1.5 m^{3} m^{-2} min^{-1}) resulted in a similar amount of photosynthesis around 20 µmol m^{-2} s^{-1}. At greenhouse without CO_2 supply also has a high photosynthetic rate when the ventilation system was open at the maximum condition to support CO_2 exchange between inside and outside. An increase in ventilation rate enhanced the photosynthetic rate value due to the enhancement of the CO_2 exchange rate of the plant canopy. The direct airflow upward or downward within a plant canopy improved the CO_2 exchange rate of the plant canopy and the consequent plant growth

(Shibuya et al., 2006). So, it can minimize the CO_2 depression in the greenhouse due to the photosynthetic process. Overall, the CO_2 supply in the greenhouse at ambient level concentration increased tomato plant photosynthetic rate at 11% compared to without CO_2 supply.

Table 4.1 Net Photosynthetic rate comparison between measured and predicted at the naturally ventilated single-span plastic house without and with CO_2 Supply (maintained at ambient level concentration) on 15th May and 5th June 2019.

Treatments	Pn * $\mu mol\ m^{-2}\ s^{-1}$	G** $m^3\ m^{-2}\ min^{-1}$	Rn** $W\ m^{-2}$	V** $m\ s^{-1}$	dCO_2** ppm	Condition PAR ($\mu mol\ m^{-2}\ s^{-1}$)
No CO2 Fertilizer						
Control (LICOR)	21.87 ± 0.55 a					Sunny day
WVB - POP	17.69 ± 1.95 a	1.342	413	0.8	-20	1300
WVB - LAI	18.54 ± 2.04 a	1.406				
CO2 Fertilizer Application						
Control (LICOR)	24.43 ± 0.64 a					Sunny day
WVB - POP	23.22 ± 0.36 a	1.059	427	1.0	35	1300
WVB - LAI	23.23 ± 0.36 a	1.054				
No CO2 Fertilizer						
Control (Measured with LICOR)	11.19 ± 0.42 a					Cloudy day
WVB - POP	9.90 ± 0.39 a	0.413	347	0.8	-26	650
WVB - LAI	9.33 ± 0.36 a	0.601				
CO2 Fertilizer Application						
Control (LICOR)	9.25 ± 0.24 a					Cloudy day
WVB - POP	10.21 ± 1.46 a	0.842	185	0.6	32.3	300
WVB - LAI	10.27 ± 1.46 a	0.838				

*Pn (photosynthetic rate), n=12, mean+SE, the numbers followed by the same letter within a column are not significantly different according to the Tukey-Kramer's test.

** Average of climate conditions: G (ventilation rate), Rn (net radiation), wind speed (v), CO_2 difference between inside and outside (dCO_2) in the greenhouse during the measurement periods on mid-day with PAR value between 300 – 1300 $\mu mol\ m^{-2}\ s^{-1}$.

The comparison between measured and predicted data are summarized in Table 4.1, containing the midday observation (between 11:00 AM – 2:00 PM). During measurement, the window aperture condition opened maximum condition both sides and roof vents with climate condition, e.g., average net radiation between 185 and 430 Wm-^{2} in cloudy and sunny day, respectively. At these conditions, the ventilation rate (G) value was between 0.843 – 1.054 $m^3 m^{-2} min^{-1}$ with outside wind velocity below 2 $m s^{-1}$. The result showed that the predicted photosynthesis using water vapor balance technique and CO_2 balance was equal with measured data. Both in the greenhouse with and without CO_2 supply, there were no significant differences between photosynthesis measurement by LICOR and predicted value using WVB-POP and WVB-LAI that combined with the CO_2 balance method ($n=12$, $P<0.05$, Tukey-Kramer's test).

Overall, monitoring of photosynthesis using a combination of CO_2 balance and the WVB technique performed in this experiment has a good result and has the same level value with the measured photosynthetic rate. The estimated Pn using the WVB-POP and WVB-LAI methods combined with CO_2 balance method has high accuracy in the presence of plants, both in the greenhouse with CO_2 fertilizer and without CO_2 supply. The results indicated that the proposed method could be applied to a commercial greenhouse for estimating the photosynthetic rate continuously.

4.4. Conclusion

Monitoring the rate of photosynthesis in tomato plants using the water vapor balance method performed quite well with the technique that has been proposed. The estimation of the ventilation rate using the WVB method had good agreement with the reference (HB method for moderately until maximum window aperture). The excellent performance of the ventilation rate contributes to estimating the net photosynthetic rate value with high accuracy. The comparison of measured and predicted photosynthetic rates indicated the same level. It can be concluded that the water vapor balance technique with the CO_2 balance model can be applied to a commercial greenhouse for monitoring the net photosynthesis continuously as representative of plant growth.

CHAPTER 5 Discussion and concluding remarks

5.1 Results considered

The work presented in the previous three chapters has enhanced the insight in the effects of the different ventilation opening areas in different seasons on the ventilation rates performance via three-type measurement methods. The following results can be considered as new contributions to the existing knowledge: data files with the ventilation measurements through a naturally ventilated single-span type greenhouse, the "heat-balance item ratio to absorbed solar radiation graph" to determine the minimum of ventilation opening area with the heat balance method, improved insight in the water vapor balance method to predict ventilation rate accurately in different variations of window aperture, a recommendation of selecting an appropriate transpiration instrument for real-time monitoring needs in the WVB method, the test of intermittent of CO_2 supply with minimum supply (between 450 – 550 ppm) for measuring the ventilation rate using decay rate method in the TG approach, validated the ventilation rate the WVB and the HB with the TG technique as a reference, and validated the measured ventilation rate via the WVB method for computing the photosynthetic rate by a portable photosynthesis device (Li-COR).

The results obtained to fulfil the main objectives and related research questions (section 1.2). Considering the ventilation rate (*G*, Chapter 2), the measurement of the ventilation rate by the TG method was presented by a set regression equation in a naturally ventilated greenhouse without crop condition. The equation or graph demonstrated the G value at different ventilation opening areas, from leakage until a high level of window aperture, in reply to the research question in point 3. In view of the aim to reply to the research question point 4 associated with the HB problem at a low ventilation opening area, the “heat balance ratio to the absorbed solar radiation” was proposed (see next section 5.2). Furthermore, in reply to research question point 5, the results indicated that the WVB has accurately predicted the ventilation rate not only at small ventilation but also at a moderate and maximum level of ventilation opening area. It performs well at optimal vapor pressure deficit conditions in a greenhouse.

The discussion on the ventilation performance under close and small ventilation level (Chapter 3) and also, under moderate and large level (Chapter 2) answers research question point 2. The WVB has better performance in continuous monitoring of the ventilation rate and has a strong correlation with the reference, the TG method, from small to a large level of ventilation opening area. It indicated that the WVB allows us to monitor the photosynthetic rate continuously in a greenhouse by CO_2 balance method. The WVB method has chosen to monitor the photosynthetic continuously and validated by Li-COR. This accurate photosynthesis calculation was presented by the WVB method combined with the CO_2 balance method, and the discussion about it was elucidated in Chapter 4. The results answer to point 1. Also, the recommendation of the transpiration device for measuring water vapor generated from crops is discussed further (see next section 5.3). The transpiration device recommendation that gave in this study has replied to the research question point 6.

5.2. The graphic method of heat balance ratio

The heat balance method has a problem of predicted ventilation rate value under the close and small level of ventilation opening area. It is tough to get good accuracy and correlation at closed and the smallest opening area (angles) due to lower solar radiation.

However, based on the results as discussed in Chapter 3, the predicted ventilation rate using the heat balance method increased in response to changes in the window opening, but it was delayed of ventilation rate value compared with the water vapor balance method due to a rapidly changed of ventilation opening area in a short time. The change in ventilation rate measured by the heat balance method was sensitive to the absorbed solar radiation.

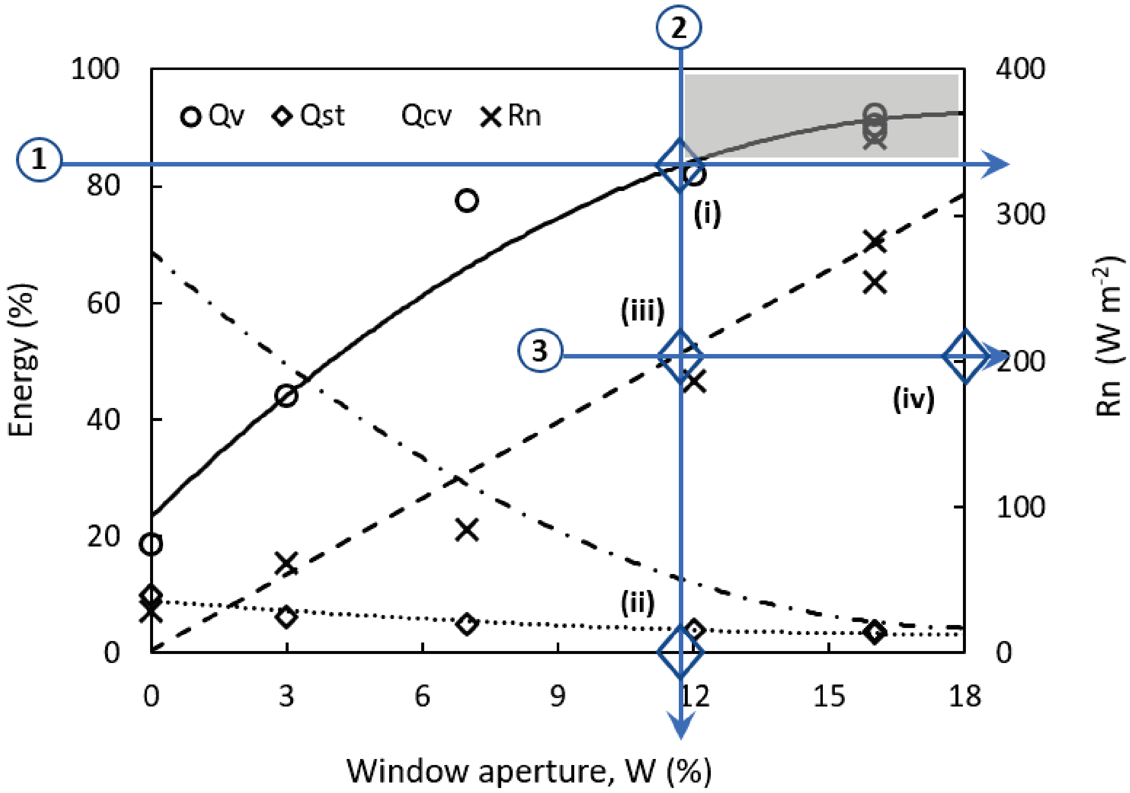


Fig. 5.1 A step-by-step process of the heat balance ratio graph for determining the minimum value of window aperture (W) and solar radiation inside the greenhouse (Rn) to perform the predicted ventilation rate accurately. Q_v is the energy removed from the greenhouse by the leakage processes and ventilation, Q_{st} is stored energy in the soil of the greenhouse floor, and Q_{cv} is thermal losses through the cover, Rn is inside greenhouse solar net radiation. A shaded rectangle is an optimal condition for the observation of the ventilation rate via the HB method continuously.

To evaluate the performance of the heat balance method for computing greenhouse ventilation rate, especially under low radiation, this study proposed the graphic method analysis for determining and assessing the minimum of net radiation and ventilation level that could predict an optimum of the air exchange rate value. The proposed method was performed and discussed in Chapter 3 under different window apertures. The proposed method can predict the optimum and the window aperture accurately. The heat balance method has excellent performance if the net radiation level started 200 W $m^{-2,}$ and the ventilation aperture is more than 10%. When the net radiation was above 200 W m^{-2}, the energy that should be removed from the greenhouse by ventilation was 81%. It is a reason why the heat balance gave better results under the larger opening area and at high radiation conditions.

How to determine the minimum of window aperture and the net radiation for computing an optimum the predicted ventilation rate based on the heat balance method? Below presented a step by step to determine those (see Fig. 5.1). Firstly, the greenhouse engineers must collect data of ventilation rate under different window apertures in their greenhouse type. There are three main parameters of energy that influenced the HB should be collected, i.e., thermal losses through cover (Q_{cv}); heat-storing in soil (Q_{st}); and the energy lost by ventilation (Q_v). All energy was absorbed from net radiation inside greenhouse (Rn). Secondly, calculate the ratio of each item of above heat balance method parameter to the absorbed solar radiation in an inside greenhouse; and then classified data into each of different ventilation opening areas, for instance: close, small, moderate, and large condition. Lastly, make a graph with x-axis as the window aperture component, the primary ordinate is the energy (in %), and the secondary ordinate is the net radiation.

Following is a step-by-step process to determine the minimum of window aperture and net radiation in a greenhouse that performs optimal the predicted ventilation rate continuously in a greenhouse.

a) Firstly, calculate the total amount of energy at close ventilation (initial point, I_0), except the energy losses from the ventilation (Q_v). $I_0 = Q_{cv} + Q_{st}$.
b) Draw a straight line (see line *point 1* in Fig. 5.1) from the initial point (a) to the right until it intersects with the energy line from Q_v (intersection node *i*).
c) From the intersection node (*i*), draw a straight line downward (line *point 2*) to intersect with the X-axis (W) as labeled with node (*ii*). Also, it intersects with a line of the absorbed solar radiation (intersection node *iii*).
d) At the intersection node (*ii*), it shows the minimum value of the ventilation opening area for a typical greenhouse that observed.
e) Whereas at the intersection node (*iii*), the minimum of solar radiation is obtained by drawing a straight line to the right side (*line 3*) until it intersects with the secondary ordinate (intersection node *iv*). This value shows the minimum value of the net radiation for a typical greenhouse that occupied.

In the upper right zone (a shaded rectangle) between above *line 1* and the right side of *line 2*, it is an optimal condition for measuring the ventilation via the HB method continuously.

5.3. Transpiration device recommendation for real-time monitoring

Transpiration rate (TR) is an essential factor in the water vapor balance method for estimating the ventilation rate in a greenhouse continuously. During an experiment in the present study, Four different methods to measure transpiration, which includes an electronic weighing device (TR_{WG}, as a control), the sap flow measurement (TR_{SF}), water level measurement (TR_{WL}), and water flow rate measurement (TR_{WF}), have been tested and evaluated on tomato crops in the naturally ventilated greenhouse (Fig. 5.2). The main goal of this evaluation 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 WVB approach.

Comparison of transpiration instruments was conducted different month (seasons), i.e., in February – April 2019 (for TR_{SF} with TR_{WG}), in October – December 2019 (for TR_{WL} with TR_{WG}), and in March 2020 (for TR_{WF} with TR_{SF}). All experiment was carried on in a greenhouse with a pot system, except comparing the TR_{WF} with the TR_{SF} that was employed in a plastic house with bed system. However, the TR_{SF} has calibrated with the control, TR_{WG}. Results obtained that the transpiration measurement with the sap flow measurement particularly accurate and has a high correlation with the control with the corresponding value of the Pearson correlation coefficients (r) was 0.89, as presented in Fig. 5.3a. While the water level device exhibited good correlation and agreement with that obtained using the weighing method, with (r) = 0.73, as presented in Fig. 5.3b. The TR_{SF} has a higher correlation than the TR_{WL}, where the TR_{WL} had scattered data linearly with an increase in transpiration.

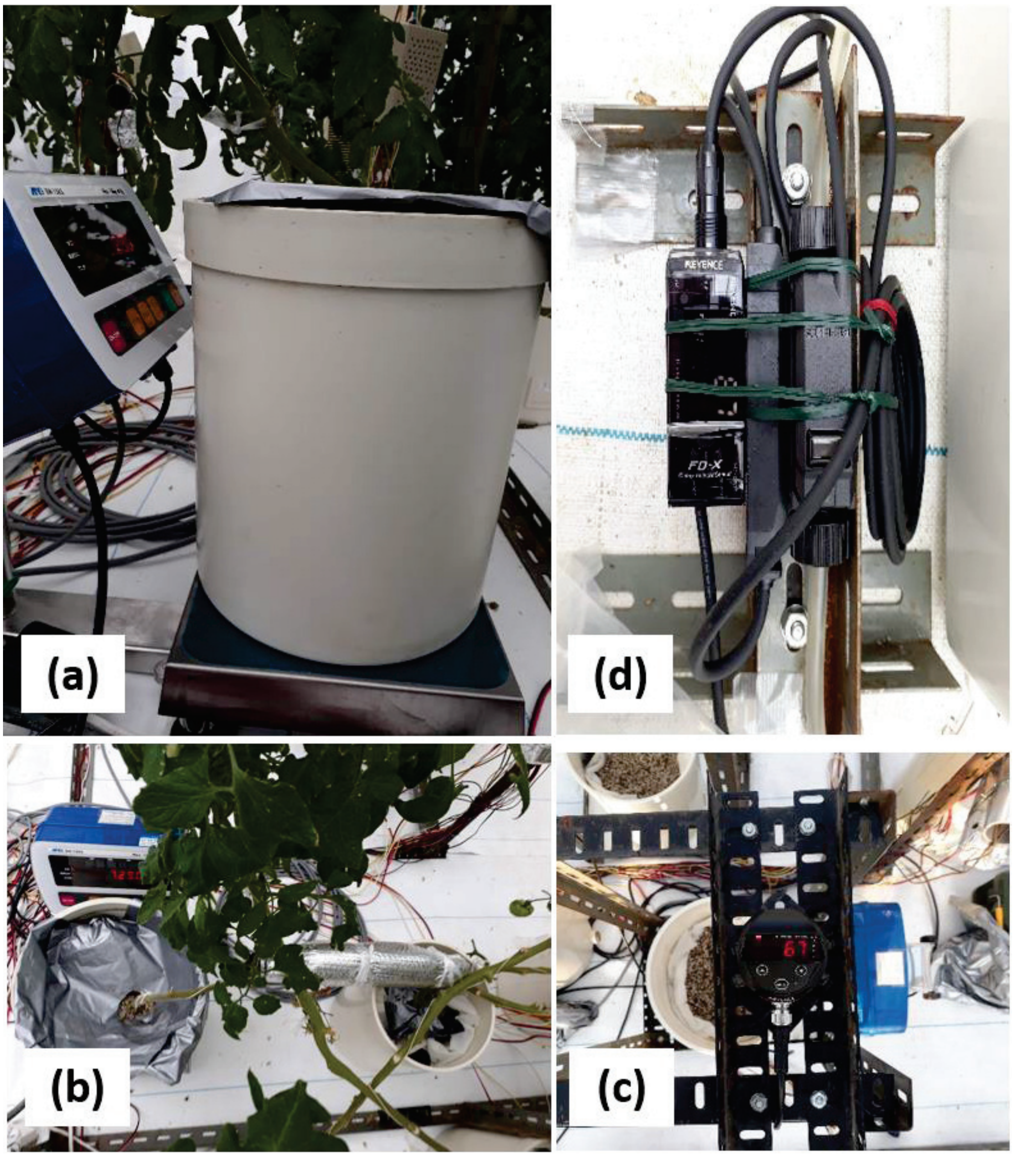


Fig. 5.2 Different transpiration instruments that evaluated during the experiment to record water vapor generated from the crops for estimating the greenhouse ventilation rate via the water vapor balance method. (a) An electronic weighing balance, (b) the sap flow measurement, (c) the water level measurement, and (d) the water flow measurement.

The TR_{WL} suffered weak agreement because it was affected by the very high sensitivity of the device to the activities in a greenhouse (shaking to the pot system). Also, in this observation, even the water level device accuracy of measurement is 1 mm. Still, if it is converted to weight unit (g), it found that 1 mm of precision device equals 18 g at

180 cm^2 of pot tomato cultivation area that used. Thus, the WL device that used suffered the long time lag of direct measurement of transpiration.

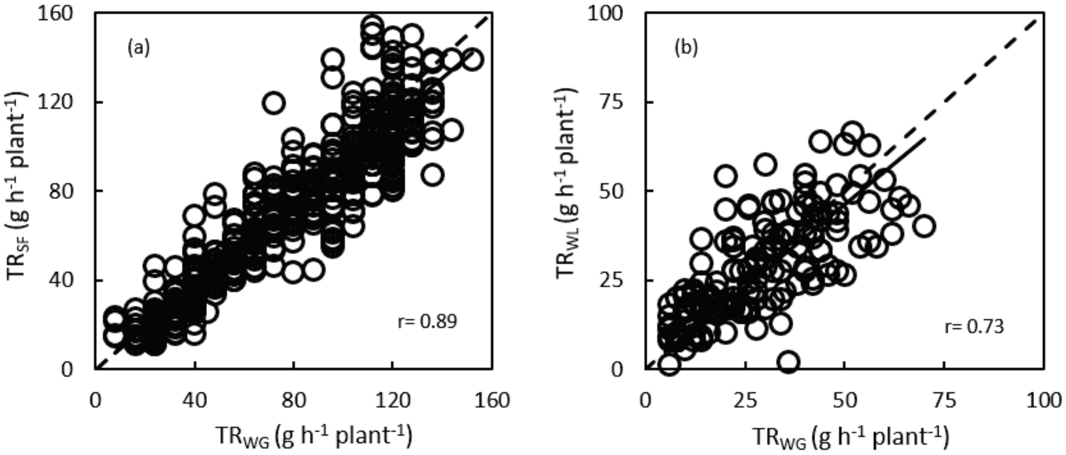


Fig. 5.3 Correlation between (a) the sap flow measurement (TR_{SF}) with the electronic balance (TR_{WG}), and (b) the water level measurement technique (TR_{WL}) with the TR_{WG}. The r value is the corresponding value of the Pearson correlation coefficient.

In contrary to the water flow measurement method, it measured the total amount of water consumption in the greenhouse. The water flow measurement has a lower correlation compared to the sap flow and the water flow with r value = 0.59 (Fig. 5.4a). The water flow technique suffered a time lag of direct measurement of transpiration, as shown in cloudy day condition (Fig. 5.4b) and sunny day (Fig. 5.4c). When the transpiration measurement via the water flow device was accumulated in the measurement day, it was sufficiently accurate and reliable for predicting the total of transpiration in the greenhouse. Thus, the water flow technique has a reasonable predicted transpiration rate in daily evapotranspiration (Fig. 5.4d).

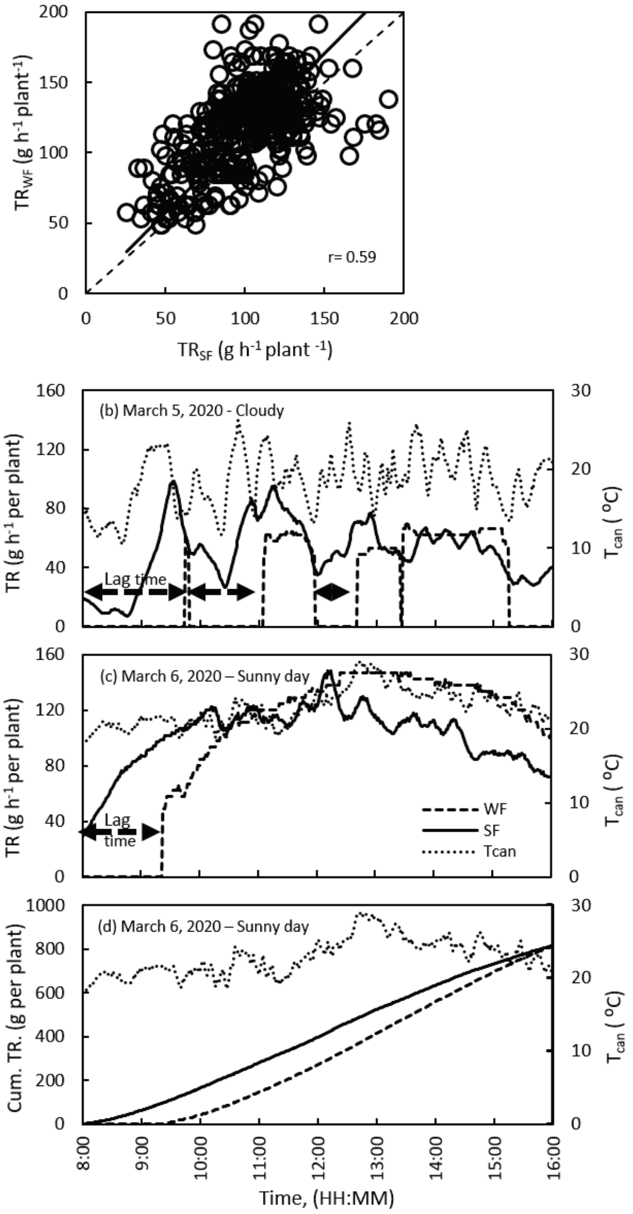


Fig. 5.4 Correlation of transpiration measurement between the water flow techniques (TR$_{WF}$) with the sap flow measurement, TR$_{SF}$ (a). Performance of the water flow sensor to measure total evapotranspiration in the greenhouse (in this chart presents per plant after divided with a total of tomato plants, 46). (b) The measured transpiration rate in a cloudy day, (c) measured transpiration rate in sunny day, and (d) the cumulative of transpiration during the day measurement on March 6, 2020.

Therefore, the study of the transpiration instrument for measuring the ventilation rate via the WVB method recommends using an electronic weighing device with high accuracy (minimum 2 g or less of precision accuracy) and the sap flow measurement for continuously monitoring of the greenhouse ventilation rate that needed to estimate photosynthetic rate.

5.4. Evaluation of the approach and recommendation for practical horticulture

At the end of this study, the pros and cons of the approach and the consequences for the validity of the conclusions are considered. The study aimed to evaluate the accuracy of the three-type measurement method of the ventilation rate in a naturally ventilated greenhouse at various levels of the window aperture. All experiments were conducted in a fully-grown tomato crop canopies in small-size of single-span greenhouse and medium-size greenhouse. The reason for using a relatively medium-size greenhouse was to achieve realistic conditions, for instance, greenhouse humidity, transpiration as a feedback effect from ventilation performance. Small-scale experiments with pot system lead to the indifference of evapotranspiration compared to the bed system, like in a medium-size greenhouse. Therefore, the response of the transpiration rate to solar radiation was restricted due to different sizes and also, material covered the greenhouse. For canopy photosynthesis and transpiration research, it is necessary to use whole canopies rather than a few plants in the pot system, as the light interception and the climatic conditions should be comparable to those in real greenhouse cultivation. However, in this study had employed and validated the transpiration rate measurement by the sap flow measurement (2 plants in a greenhouse with an area of 50 m^2) with the water flow meter (water volume consumption in a greenhouse).

For measuring the ventilation rate by the heat balance method should be considered mainly the solar radiation data collection. It is an important part of predicting the ventilation rate well by this method. In this study, the heat balance resulted from one sensor inside and outside the greenhouse. However, there was a challenge when used one sensor only in the greenhouse, because the shading effect on the sensor was present. This condition resulted in a low prediction of the ventilation rate. Therefore, it needs to consider using more than one sensor or other types of solar sensor with high accuracy. But, it is not easy to evaluate the difference of the two or more outputs.

On the contrary, the measured ventilation rate by the water vapor balance method should be considered the stage growth of the plant. In this study, the observation was conducted on a fully-grown of tomato crops for generating water vapor in a greenhouse. In advance, it needs to evaluate the WVB method in different stages of tomato crops for monitoring the ventilation rate and photosynthetic rate in a naturally ventilated greenhouse. Moreover, for the tracer gas method as a reference, the study indicated that a decreasing in the level of gas concentration CO_2 become in the range 450 – 550 ppm (the previous study used high concentration more than 1000 ppm) for predicting the ventilation rate by decay rate method gave excellent performance under different of ventilation opening area. The ventilation rate via tracer gas in a greenhouse without crops was higher than with plants. It was present due to the resistance of the airflow around the tomato crops, and also assimilation process of CO_2 in the leaves by the photosynthesis process. These are affected by the different values of tracer gas with plants and no crop conditions. Therefore, it recommends conducting the tracer gas with crop and no crop conditions together at the same time and different greenhouse. Also, it should be added to an artificial plant in a greenhouse for predicting the ventilation rate in no crop condition.

The study presents the calculation of ventilation rate via the water vapor balance method by two methods, based on the leaf area index (LAI) and population (total number of plants in a greenhouse). The LAI method has a disadvantage in practical problems. It needs to monitor the LAI every stage of growth, even in this study only measured in relatively constant of the LAI (fully-grown tomato crops). The LAI and the proposed method by population have the same level value of the ventilation rate prediction. The study suggested using the water vapor balance based on the number of plants to predict the ventilation rate due to a simple. However, this technique has considered a ratio of the canopy to the greenhouse floor area as a parameter that should be added in the method. While for measuring the transpiration rate, the study recommended for using the electronic balance with high accuracy and the sap flow measurement for monitoring the ventilation rate via the water vapor balance method. The weighing device must use an instrument with high accuracy. In this study, transpiration was observed in 2 gr accuracy of weighing. It was enough to monitor in 15 minutes. For less than 15 minutes, it is recommended to use tools with an accuracy of 1 gr or less.

On the contrary, the sap flow measurement based on the heat balance method gave data collecting in every minute. However, it should be calibrated and change the measured plant regularly to get better result measurement. During the observation, a sap flow sensor was enough for measuring in a greenhouse with an area of 50 m^2. However, it needs further study about the relation between several sensors of the sap flow to the large area of the greenhouse.

5.5. Conclusion

In general, the ventilation system in a naturally ventilated greenhouse has a significant effect on microclimate conditions, the ventilation rate, and also crop transpiration rate. This present study focused on real-time monitoring of ventilation rate for monitoring photosynthetic rate via CO_2 balance method in a naturally ventilated greenhouse. Three-type of measurement methods for measuring the ventilation rate method, i.e., tracer gas, heat balance, and water vapor balance, were compared and evaluated.

The TG, as a reference that employed with the decay rate method using CO_2 gas, showed extremely reliable for measuring ventilation rates for various ventilation opening areas. The ventilation rates using the TG method were higher when wind velocities were higher and without cultivation. However, when for a large ventilation opening area (like in late spring, summer, and early autumn seasons), a considerable amount of TG is required to maintain high and uniform concentration in a greenhouse. Furthermore, it is difficult to maintain a uniform CO_2 concentration in the greenhouse because the outdoor airflow affects the CO_2 concentration distribution in the greenhouse. Practically, it is quite difficult to implement the TG method for continuously monitoring the ventilation rate because of the above reasons and high cost.

The results obtained from the HB and WVB methods can be used for monitoring the ventilation rate for moderate and large ventilation opening areas. Both methods showed similar variation trends with time, and the ventilation rate changed considerably with the wind speed outside the greenhouse. The HB method provided accurately predicted the ventilation rate not only for the maximum window aperture but also for the moderate window aperture (more than 10%). The study found that the HB method gave better results under large ventilation opening area with solar radiation condition should be more than 200 W m^{-2}. On the contrary, the HB resulted in a lower value than the reference when the radiation was below 200 W m^{-2} or when the vents were closed and smallest of window aperture conditions, like in late autumn, winter, and early spring seasons. This problem can be elucidated using the graphic method ratio of heat balance item to absorbed solar radiation that proposed in this study—the graphic method expressed as a percentage of the net radiation collected in the greenhouse. The graphic approach of the heat balance ratio can elucidate the problem of the HB method in low ventilation. It can determine the minimum of window aperture (W), minimum of the energy should be removed from the greenhouse by ventilation, and a minimum of inside solar radiation that would give better result prediction of the ventilation rate using the heat balance method.

For measuring transpiration as a primary parameter of the WVB, the study recommended a high accuracy of electronic balance device (weighing method) and the sap flow measurements for measuring transpiration as the main source of water vapor in a greenhouse environment. The measured transpiration via the sap flow gave a better result than the flow meter and water level sensor due to the time lag of the devices used to measure transpiration. The WVB method showed reliable results through different seasons and acceptable results to several of the window aperture. The results showed the ability of the WVB method that can predict the ventilation rate not only under a small ventilation opening area but also until a high level of the window aperture. Therefore, the WVB method is suitable for the continuous measurement of the ventilation rate because it is simple and can be used for different window apertures. However, it should be noted that this method can perform well when the vapor pressure deficit in optimal condition for plants in a greenhouse. The measurement of the ventilation rate using the WVB method shows a stable response to changes in the window opening. It may permit continuous real-time monitoring of the greenhouse ventilation rates that needed to estimate the photosynthetic rate in a greenhouse.

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