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Differences between ethylene emission characteristics of tomato cultivars in tomato production at plant factory

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ABSTRACT

Ethylene is not only well known as a unique gaseous hormone, which has various impacts on plant growth, but also considered to be closely related to tomato productivity and occurrence of fruit physiological disorders. On the other hand, the different tomato cultivars were also considered as key factors influencing tomato productivity and quality. In this study, we examined the differences between ethylene emission characteristics of different tomato cultivars. Our results confirmed that the Dutch tomato cultivar 'Endeavour' emitted less ethylene compared to other Japanese tomato cultivars, whereas ethylene emission in 'Rinnka409' was significantly higher than that in other cultivars. We observed that the wounding treatment resulted in rapid increase in ethylene emission in tomato, and the increase in ethylene emission was much higher in the 'Momotarou Youku' cultivar than that in the 'Endeavour' cultivar. The results will be useful to maximize tomato productivity and reduce the occurrence of fruit physiological disorders in tomato production at plant factories.

1. Introduction

Ethylene is a well-known unique gaseous hormone, which influences plant growth over entire life of the plant, is also considered to be closely related to tomato productivity, occurrence of fruit physiological disorders, and senescence of tomato fruits [1]. Almost all organs of the higher plants can produce ethylene, although the rate of ethylene production depends on the type of tissue and the stage of development. Ethylene production will also vary in different tissues within the organ, but it is frequently located in peripheral tissues. For example, in peach and avocado seeds, ethylene production appears to be primarily localized in the seed coats, while in tomato fruit and mung bean hypocotyls, it originates in the epidermal regions [2]. In general, meristematic and nodal regions are most active in ethylene biosynthesis. However, ethylene production also increases during leaf abscission and flower senescence, as well as during fruit ripening. Furthermore, any type of wounding and physiological stresses such as flooding, chilling, disease, and temperature, or drought can induce ethylene biosynthesis [3].

Tomato (*Solanum lycopersicum*) is native to western South America and Central America. As climacteric fruit, tomato ripens in response to ethylene exhibit a characteristic respiratory rise before the ripening phase and also shows a spike of ethylene production immediately before the respiratory rise, meanwhile, treatment with ethylene induces the fruit to produce additional ethylene, its action can be described as autocatalytic. The disorder tomato fruit like fruit cracking and the wounding of tomato fruit during daily cultivation management may release much more ethylene which can cause itself and surrounding tomato fruit accelerate ripening in tomato production. In addition, it is very often to cause the mechanical injury of tomato fruit during harvest and transport, which may decrease the quality of the fresh tomato through increasing respiration and ethylene production [4].

On the other hand, tomato is considered as one of the most important vegetables in Japan due to the highest total production rate for several years. In recent years, although there are increasing number of studies on development of cultivation techniques to increase the yield [5] in Japan, tomato yield has not increased since the 1980s in greenhouse production, and remained below 30 $kg \cdot m^{-2}$ per year [6]. However, in the Netherlands, tomato production increased 5 times in 50 years [7]. To clarify this issue, Nakano et al. [8] examined the difference in yield and quality of tomato among cultivars cultivated using hydroponics in greenhouses, the results showed that higher production of tomato is usually accompanied with a decrease in soluble solid content in the fruits, which leads to low fruit quality. One of the likely reasons for the difference between Japan and Dutch tomato production is depending on

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the difference of tomato cultivars. In Japan, tomato is generally consumed directly after harvest as raw food; therefore, consumers focus on the taste of tomato, which is attributed to its soluble solid contents (sugar content). Therefore, the goal of tomato production in greenhouses in Japan is to produce the tomato with high quality with high yield [9]. In actual tomato production, many techniques like electric conductivity (EC) adjustment of nutrition solutions, environment control, etc. are adopted to adjust the growth of tomato for increasing soluble solid contents and yield of tomato, it achieved good results, but there is still quite big improvement potential on yield if cutting down the fruit disorder rate of tomato. Fruit disorder is an important factor which always accompany in the tomato production and obviously restrict the increasing of tomato yield, for the reason of tomato fruit disorder cannot be counted in yield for it is unsalable. The fruit disorder occurrence rate in tomatoes is high; on average around 18% and could even be over 35% depending on the different cultivars [8]. To achieve high tomato yield with high quality, it is important to maximize tomato productivity and reduce the occurrence of fruit disorder in tomato produced at plant factories, and to determine the key factors involved in this approach. Among tomato fruit disorders, fruit cracking takes a considerable part, which occurs both during ripening and after harvest, the occurrence rate could even be over 16% in some cultivars, and it is much easier to be restrained through water and temperature management compared with other fruit disorders. In addition, no matter during the ripening or after harvest, the ethylene emission of tomato fruit will be enhanced once the fruit cracking disorder occurred [10], which will hasten the processes associated with the ripening of tomato fruit, result in the accelerates the ripening of unripe tomato and may lead to over-ripeness of tomato fruit. Both of the above will cause the decrease in tomato quality.

In addition, different tomato cultivars exhibit different growth characteristics [8], which interact with ethylene emission during tomato production. While most of the researchers focus on the mechanism of ethylene on plants, less research is done on the plant ethylene emission, especially ethylene release amount which influences the ripening of tomato. Ethylene promotes the ripening of tomato fruit, which not only can accelerate the ripening of unripe tomato but also may lead to over-ripeness of tomato fruit. Therefore, the regulation of ethylene production in tomato fruit is important for the improvement of the shelf-life and quality of tomato [11]. Furthermore, any type of wounding and physiological stresses will increase the ethylene emission, it is important to obtain the basic information about mechanical stress on tomato ethylene emission characteristics. The aim of this study was to examine the difference between ethylene emission among different tomato cultivars and the influence of mechanical stress on tomato ethylene emission.

2. Materials and methods

2.1. Experiment location and tomato materials

The experiment was conducted at the Tsukuba Plant Factory of the National Agriculture and Food Research Organization, Tsukuba, Ibaraki, Japan (36°01′31.1″N, 140°06′02.4″E). The eave height of the plant factory greenhouse is 5.1 m and the growing area is 162 m^2 (9 m × 18 m). The roof of the entire building was covered with ethylene tetrafluoroethylene film (F-clean GR diffused type, AGC Greentech, Tokyo, Japan) and the walls were covered with glass; light transmittance was approximately 50–60% [12].

Five tomato cultivars, including 'Momotarou Youku' (Japanese cultivar, Takii & Co., Ltd.), 'Rinnka409' (Japanese cultivar, Sakata Seed Corporation), 'Zeitaku' (Japanese cultivar, Nippon Del Monte Corporation), 'Tomimarumucyo' (Dutch cultivar, De Ruiter Seeds) and 'Endeavour' (Dutch, cultivar, Rukzwaan) were seeded on August 1, 2014. After three days of processing under dark at 28 °C by hastening of germination equipment (KT-N120LAB-T, Keibun), all tomato plants were moved to the Nae terrace (Mitsubishi Plastics Agri Dream Co. Ltd.) to grow the seedlings for 21 days, then transplanted under sunlight in a plant factory greenhouse, on September 16, after secondary raising seedling in a growing room. 60 tomato plants for each different cultivar were arranged in different rows, with the planting density of 2.5 plants/m^2. Rock wool and high wire (3.4 m) cultural practice were adopted in this experiment. Fruit settings were processed by using 4-Chlorophenoxyacetic Acid (0.15%, Ishihara). The ubiquitous environment control system (UECS, Stella Green Co., Ltd.) was employed to control the environment in the growing room. The ventilation temperature for the skylight control was setting on time as following: 10 to 13 o'clock: 25 °C; 13 to 19 o'clock: 26 °C; 19 to 23 o'clock: 23 °C; 23 to 10 o'clock: 22 °C. Humidity target was set up as 50%–70% from 9 to 15 o'clock. Heating machine (Housekeon HK 2027 TEV, Nepon Inc.,) was used for making sure the temperature beyond 15 °C in greenhouse. the light shielding curtain was closed when the outdoor solar radiation was 0.8 kW m^{-2}. Insecticide and fungicide were spayed every week to prevent pests and diseases. Five plants for each cultivar were selected randomly for yield and sugar content measurement. Investigation of total yield and average sugar content of tomato by destructive investigation (PR-101α, ATAGO CO., LTD.) were conducted once a week (3 samples/week) from November in 2014 to June in 2015.

2.2. Sampling method and trait measurement

Tomato sampling was conducted on June 22, 2015, 279 days after tomato transplanting. Each five of the well-colored tomato fruits which belong to red stage ripeness were sampled for different tomato cultivars; thereafter, fruit color was measured using a spectrophotometer (CD100, Yokogawa) by using CIELAB (L*a*b* color space system, L*: from white to black; a*: from green to red; b*: from blue to yellow) color system after obtaining the fresh weight of tomato fruit. Tomato fruit volume was obtained using drainage volume measurement. Then, sugar content, acidity, and lycopene content of each tomato were measured with a portable non-destructive measurement device (Fruit selector K-BA100R, Kuboda) as the average of five measurements.

Thereafter, tomatoes were placed in a container one by one, then the six-channel flow path switching unit of a CO_2 gas analyzer (LI-800, Omron) was employed to remove air from the container until vacuum was reached, following this, stable normal air was pumped into the container using the same equipment. The container was kept in a darkroom at 25 °C for ethylene emission from the tomatoes. On June 24, ethylene concentration in the container was measured using a portable ethylene gas analyzer (CI-900, CID Bio-Science, Inc.). Then, tomatoes' weights were measured after drying in a dry machine at 105 °C for 72 h.

In addition, each ten of the well-colored tomato fruits from 'Momotarou Youku' (a typical Japanese cultivar usually for raw consumption) and 'Endeavour' (a typical Dutch cultivar usually for cooking) cultivars were sampled, and then fresh weights were measured on August 5, 323 days after transplanting. A half of each tomato cultivar was chosen randomly for scratch processing (treatment); pieces of 1.5 cm depth × 1 cm length were cut on the surface and perpendicular to the equatorial plane of each tomato, using a knife. Then, tomatoes were kept in a container; after the same process in the previous experiment by using a six-channel flow path switching unit of the CO_2 gas analyzer, all samples were placed in a darkroom at 25 °C for ethylene emission. On August 10, after measuring the ethylene concentration in each container, all samples were placed in a dry machine for drying at 105 °C for 72 h.

2.3. Calculations and statistical analyses

Ethylene measurements for tomatoes were recorded for calculating the ethylene release rate. The ethylene release rate was calculated using the following equation:

$$R = C_2H_4/W{\cdot}H{\cdot}(V - Vx), \quad (1)$$

where.

R: ethylene release rate ($nl \cdot g^{-1} \cdot H^{-1}$);
C_2H_4: ethylene concentration difference in container before and after the experiment;
W: mass of tomato sample;
V: container volume;
V_x: tomato sample volume.

Experiment data were analyzed using the analysis of variance (ANOVA) to examine variation between tomato cultivars. Mean comparisons were performed using Tukey's multiple range test (MRT) to examine whether the differences between cultivars were statistically significant ($P < 0.05$).

3. Results and discussion

3.1. Tomato fruits information

Tomato is considered as a climacteric fruit, which has two different ethylene production systems. One system functions during normal growth and development and during stress responses, whereas the other system operates during floral senescence and fruit ripening [13]. In system 1, ethylene plays a role in plant vegetative tissue by inhibiting its own biosynthesis, and therefore stabilizes ethylene synthesis (Fig. 1). In contrast, in system 2, ethylene plays a role in plant petal senescence and fruit ripening by promoting its own biosynthesis (i.e., autocatalysis) and therefore accelerates ethylene synthesis. It is challenging to establish a causal relationship between the level of endogenous ethylene and fruit ripening; even when the effects of exogenous ethylene on fruit ripening are straightforward and clear [3]. To eliminate the experimental error from the beginning and the accumulation of autocatalytic function, it is necessary to choose tomatoes of the same ripeness stage for the experiment, because ethylene emission will greatly differ depending on the ripening stage (Fig. 1).

CIE Lab was employed to evaluate the tomato ripeness stage in this experiment. Table 1 shows the basic color information about tomato fruits from different cultivars. The value of L* (lightness) was between 31 and 35, and there were no significant differences between different tomato cultivars although our measurement values were less than those of previous studies [14–17]. According to the United States standards for the grading of fresh tomato, these stages of ripeness are divided into seven levels which are 'Green', 'Breakers', 'Turing", 'Pink', 'Light Red' and 'Red' [18]. The value of a* was around 20 (between 18 and 21). There were no significant differences between different tomato cultivars, and it is considered to belong to the "Red" ripeness stage. The b* value indicated that there were significant differences between different tomato cultivars, while b* value indicated a low correlation coefficient with the maturity of tomatoes. It is considered as that both the 'Zeitaku' and 'Endeavour' belong to the red group tomato, while the 'Momotarou Youku', 'Rinnka409', and 'Tomimarumucyo' belong to pink group tomato [8]. Color grouping is decided according to the color when the tomato is ripped.

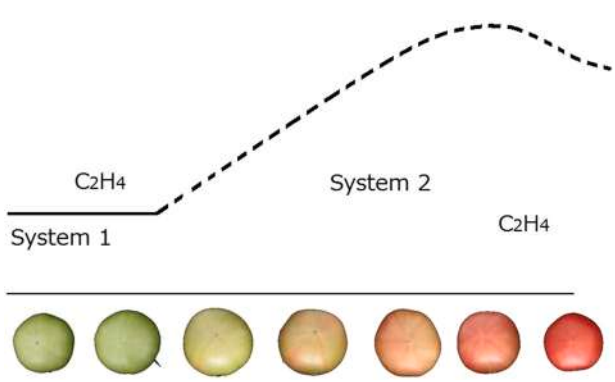

Fig. 1. Schematic diagram of two tomato ethylene synthesis systems during fruit ripening.

Japanese cultivars ('Zeitaku', and 'Rinnka409') exhibited much higher sugar content and acidity compared to Dutch cultivars ('Tomimarumucyo' and 'Endeavour'). In addition, the Japanese cultivars indicated higher lycopene content than the Dutch cultivars. The same results were obtained in the former research [8], all of that different was considered as the influence of variety characteristics of tomato. They may concern with the lower maturity rate of Dutch cultivars compared with the Japanese cultivars and the different thickness of tomato pericarp.

3.2. Ethylene release rate between different cultivars tomatoes

Owing to numerous studies on the function and mechanism of ethylene, the physiological effects mediated by ethylene in plants, including ethylene receptor, its biosynthesis, its signal transduction, and how it is regulated, are now well-understood. Much attention has been paid to tomato as a model plant, especially in relation to their functions in its ripening [13,19]. Most of the researchers have focused on the longitudinal study of ethylene through the tomato maturation process. For example, they focused on change in ethylene synthesis or release accompanied with the variety of ripening stage, and the influence of ethylene production on the changes in its physical properties (e.g., firmness and color) during ripening. However, there are few cross-sectional studies on tomato. In a study by Guillén, F. et al. [20,21], four tomato cultivars, including 'Cherry', 'Daniela', 'Patrina', and 'Raf', under two ripening stages were adopted, and they aimed to investigate tomato fruit quality retention (characteristics such as firmness, weight loss, color, and ripening) during storage by 1-methylcyclopropene (MCP) treatment as these characteristics are affected by cultivar and ripening stage at harvest. These authors investigated ethylene production in four tomato cultivars at two stages of ripening; however, they did not focus on the differences between cultivars under different ripening stages. It is difficult to distinguish the difference in ethylene production (release) between tomato cultivars.

Fig. 2 illustrates the ethylene release rate by fresh weight of different tomato cultivars. Differences were observed in the ethylene release rate in the five cultivars. Based on the experimental results, 'Rinnka409' showed the highest ethylene release rate compared to other tomato cultivars, while 'Endeavour' showed the lowest ethylene release rate. Although there was no significant difference among the other three tomato cultivars, the ethylene release rates were sequentially reduced in the order 'Momotarou Youku' > 'Zeitaku' > 'Tomimarumucyo', respectively. In the tomato production [8], the highest fruit disorder occurrence rate was observed in 'Rinnka409' cultivar, and the lowest fruit disorder occurrence rate was observed in 'Endeavour' cultivar, these well matched with the ethylene release rate of tomato. The higher ethylene release rate may result in the higher fruit disorder occurrence rate, and for the post-harvest of tomato, the higher ethylene release rate may also accelerate components (pH, Vitamin C, etc.) content changing [22], which can cause the decrease of fruit quality.

Fig. 3 shows the yield and the average sugar content of different tomato cultivars, all of which were harvested from November to June of the next year. 'Endeavour' showed the lowest sugar content and the highest yield while the 'Zeitaku' showed the highest sugar content and lowest yield, 'Rinnka409' showed the higher sugar content and lower yield. Results showed that there is no direct connection of ethylene release rate by fresh weight of yield or sugar content of different tomato cultivars.

The reverse order of ethylene release rate matched well with the order of plant height and inter-node length of these five tomato cultivars which was investigated in 2014 (Fig. 4., [8]). Is it an accidental

Table 1
Physio chemical characteristics among tomato cultivars.

Cultivars	Fruit color			Brix. (%)	Acidity[a] (%)	Lycopene (mg/100 g)	FW (g)	Dry weight rate (%)
	L*	a*	b*					
Z	32.05	21.02	25.70 a[b]	6.40 a	0.49 a	10.83	101	6.39
R	34.26	19.04	13.58 b	6.28 a	0.45 a	10.13	115	6.48
Y	33.51	19.24	14.20 b	5.22 b	0.39 b	9.81	101	4.53
T	31.65	18.58	11.98 b	4.72 b	0.35 b	7.75	144	4.34
E	31.10	20.70	27.48 a	4.49 b	0.35 b	8.57	147	4.39

Z: 'Zeitaku', R: 'Rinnka409', Y: 'Momotarou Youku', T: 'Tomimarumucyo', E: 'Endeavour.'
[a] Acidity: equivalent value of organic acid by acid-base titration method.
[b] Different letters indicate significant difference in Tukey's multiple range test ($P < 0.05$, $n = 5$).

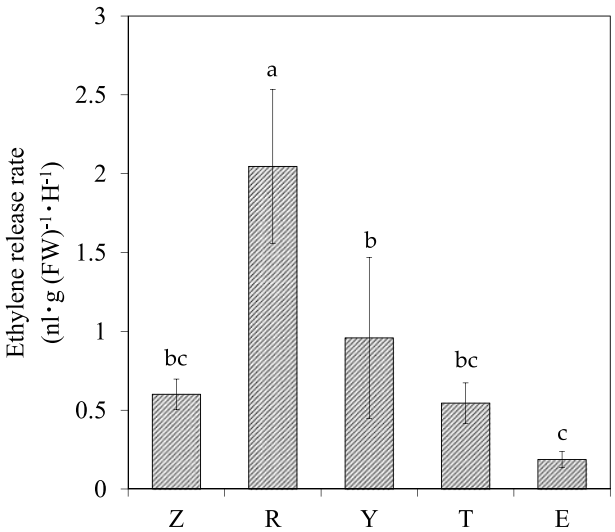

Fig. 2. Ethylene release rate by fresh weight of five different tomato cultivars
Z: 'Zeitaku', R: 'Rinnka409', Y: 'Momotarou Youku', T: 'Tomimarumucyo', E: 'Endeavour.'
Different letters indicate significant difference in Tukey's multiple range test ($P < 0.05$, $n = 5$).
Error bars in the figure represent standard deviation of data.

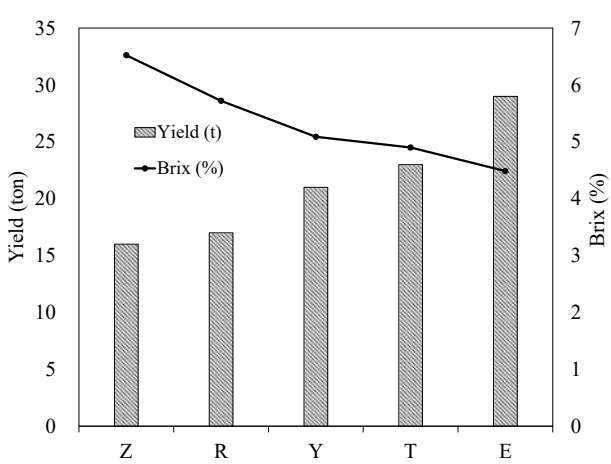

Fig. 3. Yield and average sugar content of different tomato cultivars
Z: 'Zeitaku', R: 'Rinnka409', Y: 'Momotarou Youku', T: 'Tomimarumucyo', E: 'Endeavour.'

phenomenon, or there is indeed a certain relationship, it is expected to be clarified in the follow-up study.

Fig. 5 shows the ethylene release rate by dry weight of different cultivars' tomatoes. The order of ethylene release rate did not change,

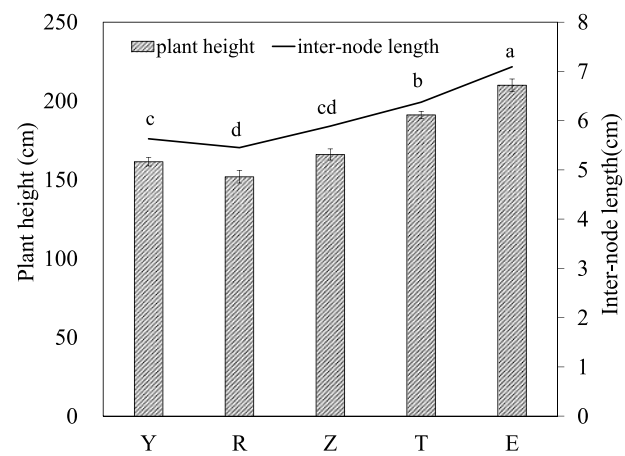

Fig. 4. The plant height and inter-node length of different tomato cultivars
Z: 'Zeitaku', R: 'Rinnka409', Y: 'Momotarou Youku', T: 'Tomimarumucyo', E: 'Endeavour.'
Different letters indicate significant difference in Tukey's multiple range test ($P < 0.05$, $n = 5$)
Error bars in the figure represent standard deviation of data [8].

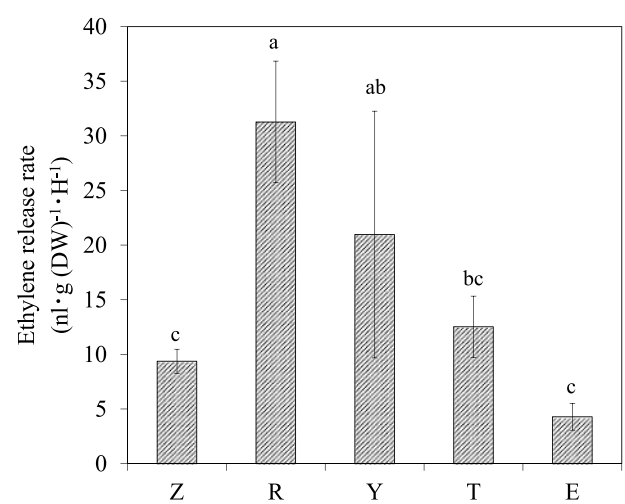

Fig. 5. Ethylene release rate by dry weight of different tomato cultivars.
Z: 'Zeitaku', R: 'Rinnka409', Y: 'Momotarou Youku', T: 'Tomimarumucyo', E: 'Endeavour.'
Different letters indicate significant difference in Tukey's multiple range test ($P < 0.05$, $n = 5$)
Error bars in the figure represent standard deviation of data.

except that the values for the tomato cultivar 'Tomimarumucyo' were greater than that for 'Zeitaku'.

'Endeavor' (a typical Dutch cultivar) indicated the lowest ethylene

release rate compared to any other Japanese cultivar. In a previous study on the occurrence of fruit disorder between these five different tomato cultivars [8], the lowest value was obtained for the 'Endeavor' cultivar compared to any other Japanese cultivar, and the highest value occurred in 'Rinnka409'. It was considered that smaller fruit enlargement and maturation rate of 'Endeavour' contributed to fewer fruit disorders. Notably, 'Endeavor' required an additional 7–10 days from flowering to harvesting compared to the Japanese varieties used in the previous experiment. These results suggest that there might be some unclarified connection between maturation rate and ethylene release rate. In addition, the 'Endeavor' cultivar has a thick and hard pericarp that can prevent fruit damage during daily management and can protect the mature fruit from damages caused by handling during harvest. Then it may be considered as the thick and hard pericarp can help to cut down the ethylene release of tomato fruit. In addition, the activity of polygalacturonase which influences the fruit firmness is regulated by calcium [23], and the generation of ethylene may increase due to calcium deficiency because of 1-Aminocyclopropane-1-carboxylic acid oxidase is controlled by calcium and calmodulin [24,25]. The higher ethylene emission was observed in Japanese cultivars compared with Dutch cultivars in this study, while in the former research the lower calcium concentration was obtained in Japanese cultivars compared with Dutch cultivars [26]. It is considered that there may exist unclear relation between ethylene emission and calcium concentration in tomato fruit.

3.3. Influence of mechanical stress on tomato ethylene release rate

Environmental stress conditions such as drought, flooding, chilling, exposure to zone, or mechanical wounding usually increase ethylene biosynthesis in plants. This increase in ethylene is produced by the usual biosynthesis pathway, which is caused by the increase in transcription of aminocyclopropane-1-carboxylate (ACC) synthase mRNA [3].

Manasikan et al. [27] studied the ethylene production rate of mature green tomato after mechanical stress treatment by dropping tomato from 5 cm height for 1 to 10 times. They confirmed that the ethylene production rate is a sensitive indicator for determining mechanical stress in tomato fruits. Furthermore, they showed that the ethylene production rate might be used as a basic screening parameter for selecting tomato fruits, and that was used in the study on the effects of chemical and physical treatments on the metabolism and quality of postharvest horticultural produce. However, they only examined the one Japanese cultivar over time.

After confirming that there is a difference in ethylene release between Japanese and Dutch cultivars, it is also very important to verify the influence of mechanical stress on tomato ethylene release rate between Japanese and Dutch cultivars, for the reason of the ethylene increasing during any type of wounding [3]. In addition, in tomato fruit, ethylene production appears to be primarily localized in the epidermal regions [2], while the skin of tomatoes is very easily damaged during harvest and transportation. In the present study, 'Momotarou Youku' (a popular and common variety in Japan) and 'Endeavour' (typical Dutch variety, high quality and yield) were used to evaluate the influence of mechanical stress on the tomato ethylene release rate. Fig. 6 shows the ethylene release rate between 'Momotaro Youku' and 'Endeavour' after the mechanical stress treatment in 1.5 cm × 1 cm (depth × length) scratch processing. The ethylene release rate significantly increased after wounding treatment in both 'Momotaro Youku' and 'Endeavour' cultivars. These increases were considered as the influence of mechanical stress because all sample tomatoes employed in the experiment were well-colored (in the 'Red' ripening stage), and at this ripening stage, the tomato ethylene release rate should decrease over time. In addition, the ethylene release rate of 'Momotaro Youku' was up to 246%, much higher than the ethylene release rate of 'Endeavour', which was only 178% (Fig. 5), compared with the ethylene release rate before wounding treatment respectively.

Fig. 7 shows the images of two different tomato cultivars cracking

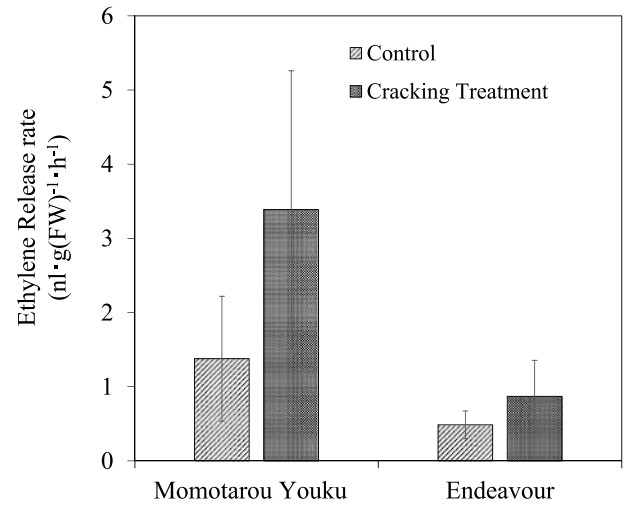

Fig. 6. Differences between the ethylene release rate of 'Momotaro Youku' and 'Endeavour' cultivars after mechanical treatment.
Error bars in the figure represent standard deviation of data.

after measuring the ethylene release rate. Before the start of the experiment, the same mechanical stress treatment was conducted on 'Momotaro Youku' and 'Endeavour' tomato cultivars. However, after the experiment, the shape of tomato cracking was different. The tomato cracking enlarged from the bottom to the top of tomato in the 'Momotaro Youku' cultivar, whereas there was almost no change in the 'Endeavour' cultivar. This was probably due to the characteristic of 'Endeavour', which has a thick and hard pericarp that prevents enlargement of the crack. Moreover, for the 'Momotaro Youku', a continuous increase in cracking size of fruit exocarp from bottom util top may cause much more mesocarp or locular tissue parts expose in the air. The ethylene produced by mesocarp and locular tissue parts of tomato much easier release to the air without obstruct by exocarp, that can cause an increase in the ethylene release rate of the 'Momotaro Youku' cultivar. Furthermore, during the tomato production and the postharvest transportation and storage, the increased ethylene release rate may cause the changing of ethylene concentration in the environment, which can accelerate fruit ripening of tomato. All of this will increase the occurrence of disorder fruit, and increase the difficulty of postharvest management, shortened the shelf time of tomatoes, and so on.

4. Conclusions

This study examined the ethylene emission of five different tomato cultivars, including three Japanese cultivars and two Dutch cultivars. The results indicated that there were differences between ethylene release rates among the five tomato cultivars. The 'Rinnka409' cultivar exhibited highest ethylene emission rate compared to other cultivars and the 'Endeavour' cultivar displayed a much lower ethylene emission rate than the others. In addition, mechanical stress can increase the ethylene release rate. The Japanese cultivar 'Momotaro Youku' exhibited a much higher growth rate compared to the Dutch cultivar 'Endeavour', which may result in faster tomato maturation or senescence. The results of this research are expected to be used to achieve higher quality and yield in tomato production, harvest, and transportation.

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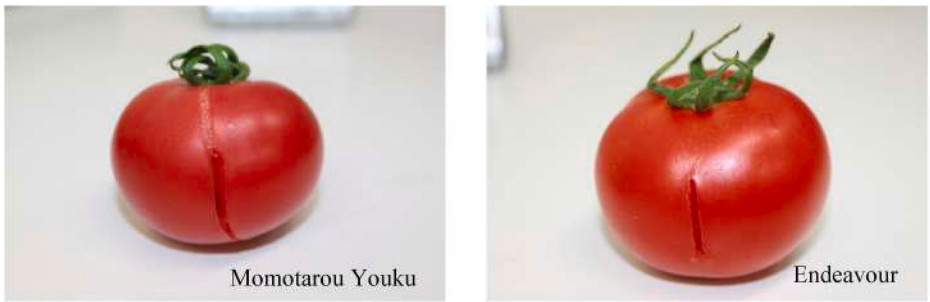

Fig. 7. Image of tomato cracking after measuring the ethylene release rate.

Author contributions

Conceptualization, Tiejun Zhao and Akimasa Nakano; Data curation, Tiejun Zhao; Formal analysis, Tiejun Zhao; Funding acquisition, Akimasa Nakano; Investigation, Tiejun Zhao; Methodology, Tiejun Zhao; Project administration, Akimasa Nakano; Writing – original draft, Tiejun Zhao; Writing – review & editing, Tiejun Zhao, Akimasa Nakano and Yasunaga Iwasaki.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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References

[1] A. Lucille, G. Don, Ethylene biosynthesis and action in tomato, a model for climacteric fruit ripening, J. Exp. Bot. 53 (377) (2002) 2039–2055.
[2] Ördög Vince, Molnár Zoltán, Plant Physiology. (Pp88-91). Debreceni Egyetem, Nyugat-Magyarországi Egyetem, Pannon Egyetem, 2011.
[3] Lincoln Taiz, Eduardo Zeiger, Ethylene, The Gaseous Hormone. Plant Physiology, in: Plant Physiology, Sinauer Associates Inc, 2004, pp. 469–538.
[4] M. Thammawong, H. Usuda, D. Nei, H. Umehara, N. Nakamura, P. Roy, T. Satake, T. Shiina, Ethylene production rate: a sensitive indicator for determining the occurrence of mechanical stress in tomato fruits, Journal of Japanese Food Preservation Science 38 (2012) 159–167.
[5] T. Higashide, E. Heuvelink, Physiological and morphological changes over the past 50 years in yield components in tomato, J. Am. Soc. Hortic. Sci. 134 (2009) 460–465.
[6] T. Higashide, K. Yasuba, K. Suzuki, A. Nakano, H. Ohmori, Yield of Japanese tomato cultivars has been hampered by a breeding focus on flavor, Hortscience 47 (10) (2012) 1408–1411.
[7] Ikeda, Present Situation and Prospect, 2013 (In Japanese), http://www.meti.go.jp/committee/materials2/downloadfiles/g90116b07j.pdf.
[8] A. Nakano, K. Shimamoto, T. Zhao, M. Arii, D. Ahn, T. Higashide, Difference of yield and quality of tomato among cultivars on hydroponics, Agric. Hortic. 91 (6) (2016) 601–607 (In Japanese).
[9] A. Nakano, T. Higashide, K. Yasuba, H. Ohmori, S. Kaneko, K. Suzuki, Research centers for intelligent plant production systems in Japan (5) national agriculture and food research organization (NARO) institute of vegetable and tea science, Tsukuba plant factory, Journal of the Japanese Society of High Technology in Agriculture 24 (4) (2012) 219–223.
[10] S. Watanabe, H. Tatsumi, T. Shinohara, K. Koshio, S. Iwahori, H. Takahashi, Effect of Ca removal from nutrient solution and diurnal variation of saturation on tomato fruit cracking and ethylene production, Food and Agriculture 6 (2009) 67–71.
[11] M. Nagata, H. Mori, Y. Tabei, T. Sato, M. Hirai, H. Imaseki, Modification of tomato ripening by transformation with sense or antisense chimeric 1-aminocyclopropane-1-carboxylate synthase genes, Acta Hortic. (394) (1995) 213–218.
[12] T. Higashide, T. Oshio, T. Nukaya, K. Yasuba, A. Nakano, K. Suzuki, H. Ohmori, S. Kaneko, Light transmission of a greenhouse (NARO Tsukuba factory farm) built to meet building and fire standards, NIVTS 13 (2014) 27–33.
[13] C.S. Barry, J.J. Giovannoni, Ethylene and fruit ripening, J. Plant Growth Regul. 26 (2) (2007) 143–159.
[14] A. Camelo, G. Perla, Comparison of color indexes for tomato ripening, Horticultura Brasileira, Brasília 22 (3) (2004) 534–537.
[15] P. Viskelis, J. Jankauskiene, R. Bobinaite, Content of Carotenoids and Physical Properties of Tomatoes Harvested at Different Ripening Stages, in: Foodbalt, 3rd Baltic Conference on Food Science and Technology, 2008, pp. P166–P170. Jelgava, Latvia.
[16] A. Radzevičius, P. Viškelis, J. Viškelis, R. Karklelienė, D. Juškevičienė, Tomato fruit color changes during ripening on vine, International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnological Engineering 8 (2) (2014) 112–114.
[17] R. Arias, T. Lee, L. Logendra, J. Harry, Correlation of lycopene measured by HPLC with the L*, a*, b* color readings of a hydroponic tomato and the relationship of maturity with color and lycopene content, J. Agric. Food Chem. 48 (5) (2000) 1697–1702.
[18] USDA, United States Standards for Grades of Fresh Tomatoes p4, United States Department of Agriculture, Agriculture Marketing Service, Washington, DC, 1991.
[19] N. Nakamura, B. Xu, M. Thammawong, H. Ito, M. Kitagawa, T. Inakuma, T. Shiina, Prediction of color and firmness changes in mature green tomato (cv. Momotaro) during ripening by cumulative ethylene production, Food Preservation Science 36 (2) (2010) 67–74 (In Japanese).
[20] F. Guillen, J.M. Valverde, D. Martinez-Romero, S. Castillo, D. Valero, M. Serrano, Tomato fruit quality retention during storage by 1-MCP treatment as affected by cultivar and ripening stage at harvest, V International Postharvest Symposium 682 (2004) p1069–1076.
[21] F. Guillén, S. Castillo, P.J. Zapata, D. Martínez-Romero, D. Valero, M. Serrano, Efficacy of 1-MCP treatment in tomato fruit, 2. Effect of cultivar and ripening stage at harvest, Postharvest Biol. Technol. 42 (3) (2006) 235–242.
[22] S. Chomchalow, N.M. El Assi, S.A. Sargent, J.K. Brecht, Fruit maturity and timing of ethylene treatment affect storage performance of green tomatoes at chilling and nonchilling temperatures, HortTechnology horttech 12 (1) (2002) 104–114.
[23] C. Lu, C. Liu, Q. Shen, H. Liang, Effect of the calcium on polygalacturonase (PG) activity and synthesis at different ripening stages of tomato fruits, J. Integr. Plant Biol. 32 (11) (1990) 858–863.
[24] K. Tanaka, M. Yokota, Y. Ishikawa-Takano, T. Asakura, K. Miyairi, T. Okuno, Role of calcium in fruit involved in ethylene production, Acta Hortic. 464 (1998), 504-504.
[25] K. Tanaka, T. Asakura, N. Muramatsu, Role of calcium and calmodulin on ethylene production in apple fruit, Biochemistry 39 (2000), 1564-1564.
[26] A. Nakano, T. Higashide, D. Ahn, Relationships between yield, mineral content of fruits, and sap bleeding rate in Dutch and Japanese tomato cultivars, Jpn. Agric. Res. Q. 51 (1) (2017) 69–75.
[27] T. Manasikan, H. Usuda, D. Nei, H. Umehara, N. Nakamura, P. Roy, T. Satake, T. Shiina, Ethylene production rate, A sensitive indicator for determining the occurrence of mechanical stress in tomato fruits, J. Food Process. Preserv. 38 (2012) 159–167.