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A Study on Factors Affecting High Quality Fruit Tomato Production in a Greenhouse by Utilizing Low Cost Smart Agriculture Framework

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ABSTRACT

In this paper, we present an examination of factors affecting the sweetness degree of fruit tomato by utilizing a low-cost smart agriculture framework. Japanese consumers are willing to pay a sky-high price for particularly high sweetness degree of tomato, known as fruit tomato. Japanese farmers would like to produce sustainable fruit tomato, yet only some of the veteran farmers with tens of years of experience or big industrialized farms can produce it. Small scale farmers still struggle to produce sustainable fruit tomato. Many of them would like to know what factors affecting the sweetness degree of tomato. This study aims to clarify factors affecting the sweetness degree production by using a low-cost smart agriculture framework installed in a fruit tomato farmer in Nara prefecture, a western part of Japan. The data used were automatic data gathered from the sensor network, i.e. temperature, humidity, atmospheric pressure as well as CO_2; and manually input cultivation records, namely, fertilizers (Ca, NO_3), pH, EC (electrical conductivity), harvesting record (yield and sweetness degree) as well as cropping calendar. We gathered data from June 2017 to December 2019. We then conducted a statistical analysis using the R statistical computing language. We found that the most significant factor for a high sweetness degree of fruit tomato is the growing time, that is the longer the growing time, the higher the sweetness degree of fruit tomato. The growing time is likely to be affected by season, as in summer growing time is faster than in wintertime. Consequently, summer is not the best time to grow fruit tomato.

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1. INTRODUCTION

Tomato (*Solanum Lycopersicum L.)* is one of the most consumed vegetables in Japan (MAFF, 2019). According to the report, Japan's per capita consumption of tomatoes amounted to 10kg in 2018. Tomato production was also ranked number one in terms of value among other vegetables listed in the Japanese market, with a value of 240 billion JPY (approximately 2.2 billion USD). In terms of volume, tomato farmers in Japan produced 722,400 ton. Although tomato is a fruit, in Japan, it is categorized as a vegetable, specifically called fruit vegetable (MAFF, 2018b).

According to (Higashide et al., 2012), Japanese consumers and retailers prefer quality such as the sweetness degree and appearance (scratches, colors, and shapes) rather than quantity. (Izawa, 2014) surveyed rank consumer preferences of Japanese consumers toward agricultural products. Unsurprisingly, tomato was the first preference of Japanese consumers for five consecutive years (2009 to 2013). In response, Japanese farmers attempt to put much effort to produce high-quality sweet tomatoes to meet the demand from the consumers (Amano, 2020). Specifically, (Amano, 2020) stated that numerous Japanese tomato farmers possess a nondestructive refractometer to carefully measure the sweetness degree of every single tomato to make sure that they ship the best quality of tomato. Then they sort the harvested tomato based on the size as well as the sweetness degree, pack them and finally ship or sell them. In Japan, a particularly sweet tomato is usually called fruit tomato (Ayabe et al., 2009; MAFF, n.d.). According to the same reports, while the average sweetness of typical tomato in Japan is 4, there is currently no specific definition of fruit tomato. However, several Japanese consumers and farmers consider a sweetness degree of 7 to be the threshold of fruit tomato (Amano, 2020).

Japanese tomato farmers would like to produce sustainable high-quality fruit tomato simply due to the expensive price. Explicitly, in 2018 the market price of one plastic bag of tomato consists of three tomatoes (about 230 g) with unmeasured sweetness degree is 86 JPY, fruit tomato-labeled with sweetness degree less than 7.0 is 300 JPY, for sweetness degree between 7.0 to 8.4 is 500 JPY, 8.5 to 9.9 is 600 and for sweetness degree, more than 10.0 is 700 JPY (Amano, 2020; Rubanga et al., 2019). Tomato with the highest quality is 8 times more expensive than tomato with the lowest quality. In other words, the higher the sweetness degree, the more expensive the price is. We can understand why Japanese tomato farmers would like to produce a higher quality of tomato rather than a higher yield. Some of the veteran farmers with tens of years of experience or big industrialized farms can produce sustainable high quality of fruit tomato, yet small scale farmers still struggle to produce sustainable high quality. Many of them would like to know what factors affecting the sweetness degree of tomato. Consequently, an investigation of factors affecting the sweetness degree of tomato is necessary.

Several previous studies suggested that water stress is a significant factor for the sweetness degree of fruit tomato (Manishi, K., Fukumoto, Y., Yoshida, 1996; Terasawa et al., 2008). Another experiment conducted by (Ibaraki Prefectural Government, 2010) suggested that CO_2 also affects the sweetness degree of fruit tomato. However, their studies were conducted in laboratories by researchers and not in an actual field by farmers. Generally, an experiment in laboratory and real-world farming in the field are different (Hansson, 2019). Besides, their studies only emphasized on one specific factor.

Other than water stress and CO_2, farmers would also like to know the impact of other factors, such as microclimate in the field (temperature, humidity, and pressure), fertilizers, cropping calendar, and yield to sweetness degree of fruit tomato. Those factors are important because, in the field, farmers concern about managing those factors from their experience and tacit knowledge for years. For those reasons, it is necessary to conduct a study on factors affecting the sweetness degree of fruit tomato with the involvement of farmers by monitoring several factors potentially affecting the sweetness degree in the field.

On the other hand, smart agriculture is generally considered to be a cutting edge that can help farmers to produce sustainable high-quality products (Okayasu et al., 2018; Opara, 2004; Tong-Ke, 2013). Principally, smart agriculture helps farmers to monitor many aspects of the farming, and it can be used to monitor factors potentially affecting the sweetness degree of tomato. However, the cost of smart agriculture is not cheap. Farmers need to spend several millions of JPY for the installation cost, not to mention the monthly cost of maintenance and administration (MAFF, 2018a). Such kind of expensive costs can only be borne by big and industrialized farms (MAFF, 2018a; Okayasu et al., 2018). If this situation continues small scale farmers will not be able to implement smart agriculture. Eventually, they cannot produce high-quality agricultural products and cannot compete with big and industrialized farms. Therefore, a low-cost system to implement smart agriculture is necessary.

The problem of smart agriculture implementation is also faced by many Japanese tomato farmers. Many of the tomato farmers in Japan are considered as small-scale farmers, with the average of tomato farm acreage of only 60a, while most of them produced in a greenhouse (SBJ, 2020). The farmers would like to utilize smart agriculture to produce sustainable high-quality fruit tomato, yet they cannot bear the cost. To deal with the stated problem, our previous research developed a low-cost smart agriculture system for small scale greenhouse farming (Rubanga et al., 2019). Specifically, we developed the base of low-cost monitoring frameworks such as input system for farmer's data (fertilizer, yield and cropping calendar), microclimate network sensor installment, real-time data transmission system, database construction, and website for visualization. We then deployed our low-cost monitoring framework in a greenhouse of fruit tomato owned and managed by farmers. Moreover, we also determined microclimate spatiotemporal distributions using heat unit in growing degree day (GDD) (Snyder et al., 1999) which showed well-defined microclimate variations within the greenhouse. However, analysis of data to investigate factors affecting the sweetness degree of fruit tomato has not been conducted. Thus, in this paper, we would like to utilize our low-cost monitoring system to investigate what factors affecting the sweetness degree of fruit tomato as the next step of our research.

In this paper, we worked together with farmers in an actual field by utilizing our system to monitor and accumulate microclimate data, fertilizers, cropping calendar as well as yield records instead of only monitoring one specific factor. Next, we analyzed the data to investigate what factors affecting the sweetness degree of fruit tomato as the next step of our research by using statistics. By clarifying which factors affecting the sweetness degree of fruit tomato, we can support small scale fruit tomato farmers by providing scientific reference.

2. MATERIALS AND METHOD

We deployed our framework and data gathering in our previous study. In this study, we utilized the gathered data to investigate factors affecting the sweetness degree of fruit tomato. The flowchart of the research methodology is shown in **Figure 1**. First, we conducted a selection of variables (factors). Next, we did the determination of the fruit tomato cultivation cycle and the derivation of independent variables. After that, we applied statistical data analysis to conduct independent variable selection, standardization of variables as well as investigation of factors affecting sweetness degree simultaneously. Statistical data analysis is described in section 2.3.

2.1. Automatic and manual farming information

We gathered two types of data input for this study, automatic data input from the sensor network and manual data input by farmers. Both types of data are stored in a cloud system (see **Figure 2 (a)**). The automatic data is obtained by a low-cost sensor network called Netatmo, which was installed within the greenhouse (see **Figure 2 (b)**). Data obtained by the Netatmo sensor network consists of temperature, humidity, atmospheric pressure, and CO_2 and are sent at five-minute intervals to the server. For the manual data input by farmers, the farmer input the record of fertilizer amount (Ca and NO_3), pH, electrical conductivity (EC), water stress, harvesting records (yields and average sweetness degree each harvest), and cropping calendar to google drive. Next, we combine, store, and manage all the data in a database. We use the data to analyze and give feedback to the farmers. We gathered the above-mentioned data from June 2017 to December 2019, in which 16 cropping cycles data is available for the analysis.

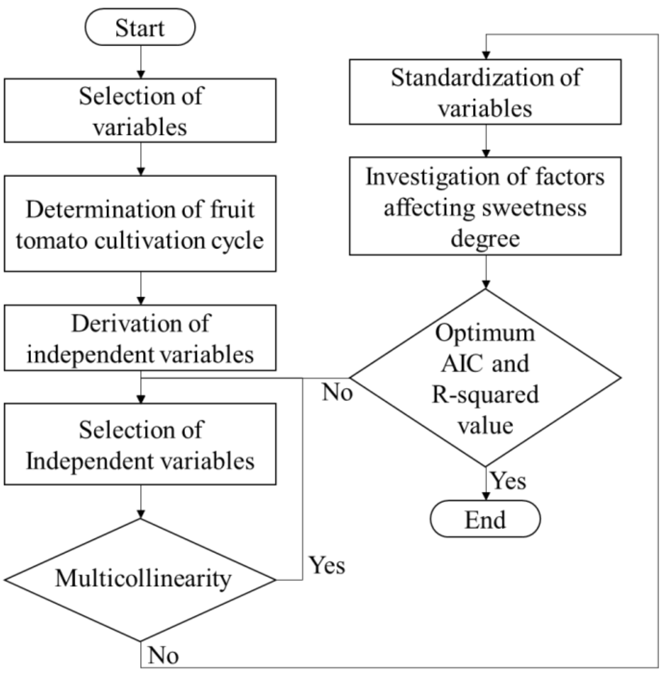

Figure 1. Flowchart of research methodology.

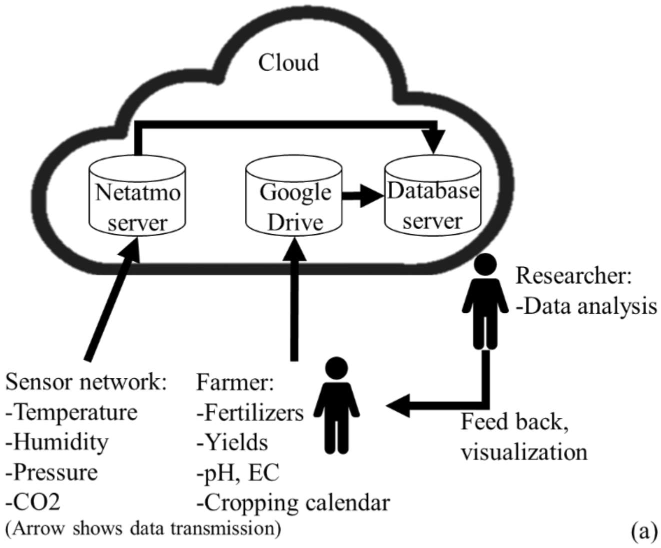

Figure 2. Sketch of the automatic and manual data collection and transferring scheme in this study (a). Sensor network in T farm's greenhouse (b).

2.2. Study area

In order to investigate the factors affecting the sweetness degree of fruit tomato, we work together with a tomato farm called T farm where we have installed our previous system (Rubanga et al., 2019). T farm is a farm that produces fruit tomato located in Nara Prefecture, the western part of Japan (see **Figure 3**). In T farm, tomato farming is conducted in a 30a of the greenhouse using a hydroponic system. The farmers in T farms have been conducting fruit tomato farming for hereditary since several decades ago. From our interview in 2019, we noticed that they usually conducted farming based on intuition and empirical procedure gained from their experience, However, several productions did not go as their expectation, i.e. the sweetness degree of their product is below 7.0. Even though they have a rich experience, they are still interested to know factors affecting the sweetness degree of fruit tomato scientifically.

2.3. Statistical data analysis

To determine factors affecting the sweetness degree of fruit tomato production, the first step was variable data standardization and then multiple regression analysis (MRA). The data analysis in this study was conducted using the R statistical computing language. Variable data standardization is important to make sure that all independent variables are on the same level of scale. By conducting standardization, we can compare them directly and determine influential factors affecting the sweetness degree of fruit tomato during MRA. To do data standardization, we implemented z-score scaling (Gower, 1985; Johnson, R. A., Wichern, 1992) for all independent variables. Raw independent variables values (x) are converted into a standard score (z) by Eq (1),

$$z = \frac{x - \mu}{\sigma} \quad (1)$$

where μ is the mean of each independent variable and σ is the standard deviation. As a result, all independent variables in the data set have equal means (0) and standard deviations (1).

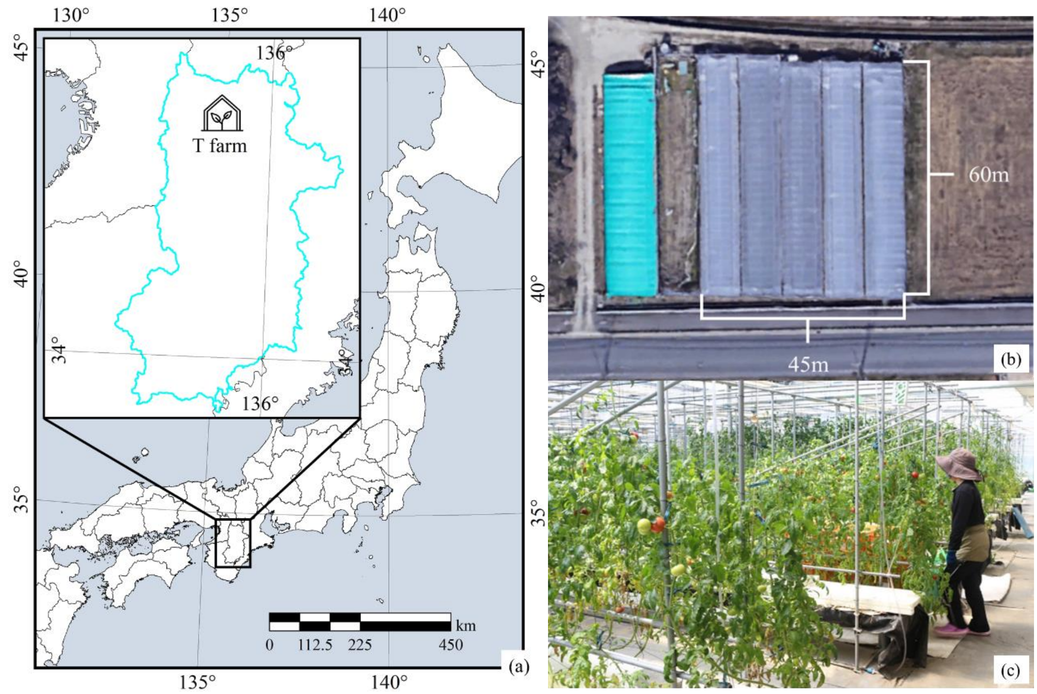

Figure 3. T farm location in Nara prefecture (a). Aerial picture of greenhouse (b). Hydroponic tomato block in T farm's greenhouse (c).

We then conducted MRA of average sweetness degree by several independent variables organized from the data input. The MRA is conducted to examine influential factors of sweetness degree of fruit tomato (Anderson, D. A., Sweeney, D. J., Williams, 2008). The regression model is given by Eq. (2),

$$Y = \beta_0 + \sum_{i=0}^{n} \beta_i z_i \quad (2)$$

where Y indicates the average sweetness degree of harvested fruit tomato for each cropping cycle, n is the number of independent variables, β_0 is intercept, β_i is i-th estimate coefficient and z_i is i-th independents variable.

However, we need statistically significant independent variables to reduce overfitting possibility as well as to determine the most optimum regression model possible in this study. This can be obtained by variable selection (James et al., 2013). Variable selection can be conducted by several ways namely, exclusion of independent variable after computing correlation value of each variable to prevent multicollinearity (Farrar & Glauber, 1967); exclusion of independent variable by considering coefficient value, p-value and R-squared value in the generated regression model (Anderson, D. A., Sweeney, D. J., Williams, 2008); independent variable combination and exclusion based on AIC (Akaike information criterion) value (Akaike, 1974; Bedrick & Tsai, 1994); and consideration of variable selection based on previous studies and based on farmers' empirical experience. With these in mind, it is important to conduct MRA repeatedly while conducting variable selection until we get the most optimum regression model possible.

3. RESULTS AND DISCUSSION

3.1. Variables selection

After conducting the examination of variable selection, we decided to use EC instead of fertilizers (Ca and NO3) and pH. This exclusion is due to a strong correlation between EC and fertilizers as well as pH. Strong correlation between independent variables will lead to multicollinearity (Farrar & Glauber, 1967). This phenomenon is unsurprising as EC value is generally known to be affected by the number of nutrients (input of fertilizers) in the water. Besides, the function of the mentioned fertilizers is to control pH and to prevent blossom-end rot (CHO et al., 1992; Yoshida, Y., Shingai, A., Ooyama, M., Murakami, K., Goto, 2013), without having any impact on the sweetness degree of fruit tomato. Therefore, we excluded fertilizers and pH as our MRA variable and used EC instead.

3.1.1 Derivation of independents variables from EC

We also found that EC is an important variable because through EC we can monitor the cultivation cycle of fruit tomato as well as deriving several independent variables for this study. The changes in the EC value of one cultivation cycle in our study is shown in **Figure 4**. The blue line is the EC value record and the red dashed line is the trend line of EC value. The trend of EC value in a cropping cycle is a sigmoid-shaped curve. One cultivation cycle is started by seedling, after that tomato plant will eventually start growing until it reaches a mature stage at some point, then it will come to the end of the production cycle. Based on our interview, most of the tomato farmers in Japan will cut down the tomato plant at the end of the production cycle to make sure the tomato they produce is in the highest quality possible. As we can see, EC value changes along with the growth of fruit tomato. When the tomato plant starts to grow, the EC value rises rapidly until reaching a mature stage, when it matures EC value is sloping towards the end of the production cycle.

In this study, EC data is then derived as several variables, namely growing time, number of days of growing time, simply computed by subtracting the day when it reaches the mature stage and when it starts to grow; growing time slope, computed by derivation of EC value change during growing time and overgrowing time; cultivation time slope, computed by derivation of EC value change during cultivation time and over-cultivation time; average, maximum, minimum and standard deviation of EC value both in growing time and cultivation time.

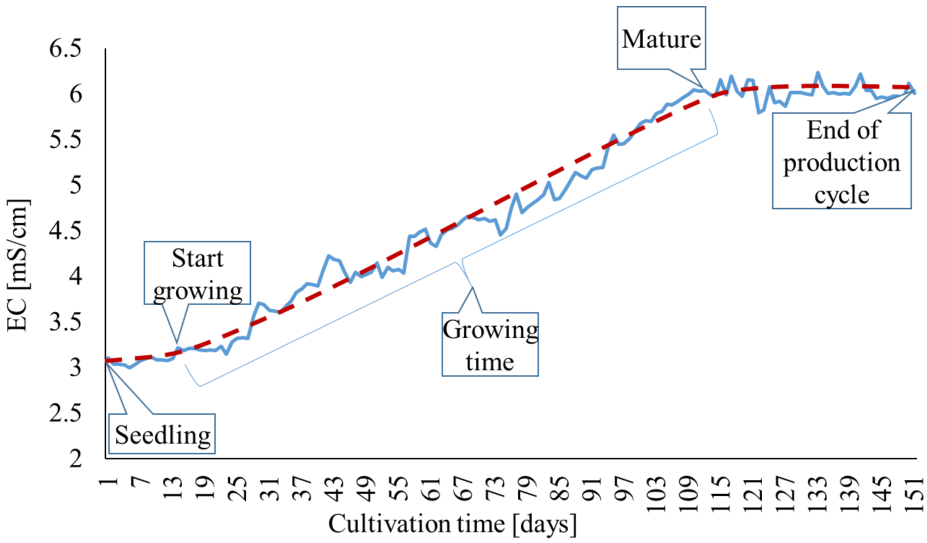

Figure 4. EC characteristics throughout one cropping cycle.

3.2. Statistical data analysis results

Next, we conducted independent variable selection while considering the coefficient values of each independent variable, R-squared value, and AIC value repeatedly. The independent variables we used to construct regression model are several variables derived from EC; accumulation of daily average temperature, humidity, air pressure, CO_2 and water stress during cultivation time; average, maximum, minimum and standard deviation of temperature, humidity, air pressure, CO_2 as well as water stress during cultivation time; and accumulation of yields.

3.2.1. MRA results on investigation of sweetness degree of fruit tomato

After various examination of variable selection and standardized model construction, we got the most optimum regression model to determine factors affecting the sweetness degree of fruit tomato production. The summary of our regression model is shown in **Table 1**. The adjusted multiple R-squared is 0.9051, which means independent variables in this model can explain approximately 90% variability of sweetness degree of fruit tomato production. In other words, four independent variables in **Table 1** can explain 90% of the sweetness degree of fruit tomato production in this study. Whereas AIC value for this model is 13.10737.

From the MRA result of the sweetness degree of fruit tomato production, we can see that there are two most significant factors affecting the sweetness degree of fruit tomato. Specifically, the significance level (α) of the growing time was below 0.001, and cultivation time was 0.01.

It points out that the most statistically significant factor affecting the sweetness degree of fruit tomato production in this study is the growing time. It means the longer the growing period, the probability of producing sweeter fruit tomato is higher as well. The growing time will be discussed in more detail in section 3.3.

Cultivation time also plays an important role, that is the longer the cultivation time, the probability of producing sweeter fruit tomato is higher as well. Next is CO2 with α of 0.1. While CO2 is generally known for its role of photosynthesis and glucose production in a plant, we found out that the CO2 level should not be too high because the higher the CO2 level, the probability of producing sweeter fruit tomato is lower. This result is in line with an experiment conducted in 2010, in Ibaraki prefecture, Japan (Ibaraki Prefectural Government, 2010).

Table 1. Summary result of multiple regression analysis of sweetness degree of fruit tomato production

Variables		Estimate β_i	Std. Error	T-value	Pr(>|t|)	α
β_0	Intercept	7.53290	0.07553	9.739	< 2e-16	
z_1	Growing time	0.61848	0.12402	4.987	0.000411	***
z_2	Cultivation time	0.65096	0.18156	3.585	0.004280	**
z_3	Accumulation of CO2	-0.31088	0.16530	-1.881	0.086736	.
z_4	Accumulation of water stress	-0.08050	0.08979	-0.897	0.389130	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3021 on 11 degrees of freedom. Multiple R-squared: 0.9304, Adjusted R-squared: 0.9051. F-statistic: 36.78 on 4 and 11 DF, p-value: 2.631e-06.

The last independent variable is water stress, which we found to be not statistically significant. However, previous studies reported that water stress is a significant factor for the sweetness degree of fruit tomato (Manishi, K., Fukumoto, Y., Yoshida, 1996; Terasawa et al., 2008). The difference could be due to the following: T farm mainly produces fruit tomato, therefore the water stress is set for that specific product, while in the studies (Manishi, K., Fukumoto, Y., Yoshida, 1996; Terasawa et al., 2008) water stress was measured in an experiment with significantly different level.

3.3. Growing time and sweetness degree of fruit tomato

As the most statistically significant independent variable in this study, growing time plays a very important role in the sweetness degree of fruit tomato. We then investigated in more detail about the relationship between the growing time and the sweetness degree of fruit tomato (see **Figure 5**).

In the graph of **Figure 5**, we can see that the longer the growing time, the sweeter the fruit tomato will be. This is shown by the R-squared value of 0.8496. We also suspect that physically it will reach a peak to some extent because tomato will rot naturally when it is not harvested. Therefore, a three-degree polynomial trend curve was constructed. The continuation of data collection, as well as more comprehensive examination regarding this issue, is necessary and it should be conducted as the next step of this study.

To examine the similarity and difference between the high and low sweetness degree of fruit tomato production, we plotted several EC value of cropping cycles in **Figure 6**. The lines in **Figure 6** indicate EC values, whereas callouts boxes indicate the sweetness degree and the start/end of growing time. The growing time of fruit tomato with a sweetness degree less than 7 passes through summer (Summer in Japan lies between June to September). We then interviewed the farmers on T farm, and we found that rich experienced fruit tomato farmers empirically know that summer is not the best time to grow fruit tomato. Moreover, this phenomenon is contradictory with the largest producers of tomato in several parts of the world where most of them start to cultivate and grow a tomato in early summer, such as in China (Xu et al., 2000), India (Bhanti & Taneja, 2005), U.S. (Selina, P., Bledsoe, 2002) and Egypt (El-Gizawy et al., 1993).

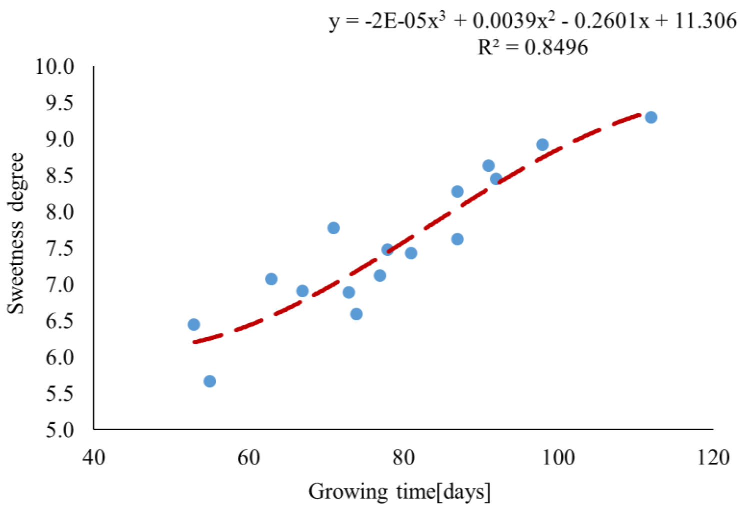

Figure 5. Relationship between growing time and sweetness degree.

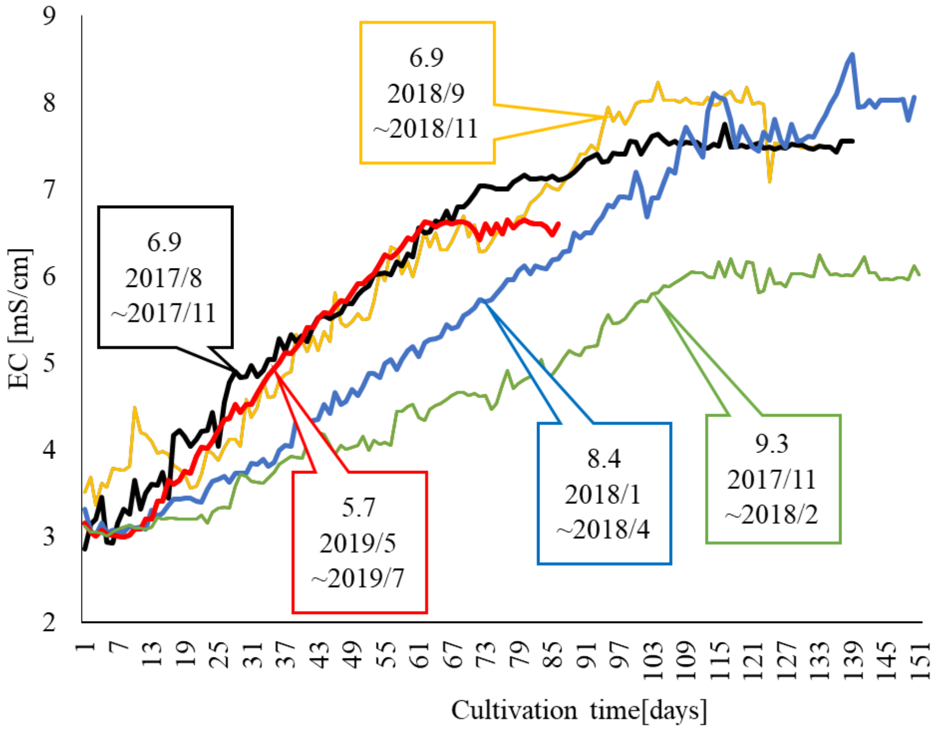

Figure 6. Plotted EC value of several cropping cycles.

It seems that there is a relationship between season and growing time, which eventually affects the sweetness degree as well. According to (Yoshino, M. M., Kai, 1977), summer in Japan has a characteristic of long sunshine duration (more than 14 hours of sunshine duration), hot (average temperature approximately 30 °C) and humid (average temperature approximately 70%). Those conditions make a tomato plant to grow fast (Nagaoka, M., Takahashi, 1983; Saito & Ito, 1967). That is why fruit tomato that grows in summer tends to have a shorter growing time. This is consistent with our findings that the shorter the growing period, the lower the sweetness degree of fruit tomato.

Based on this result, we show the scientific evidence of the empirical knowledge stated above, i.e. when the growing time of fruit tomato passes through summer, the sweetness degree is lower than in winter. With that in mind, the farmers should adjust the seedling and growing time not to pass through summer to gain the most optimum sweetness degree of fruit tomato. When farmers constrain to pass through summer, it is better to use an air conditioning system for controlling microclimate within the greenhouse, which eventually controls the growing time of fruit tomato.

4. CONCLUSION

In this paper, we have presented an investigation on factors affecting the sweetness degree of fruit tomato by utilizing a low-cost smart agriculture framework. The study showed that the low-cost smart agriculture framework used in this study can help to identify factors affecting the sweetness degree of fruit tomato. The most statistically significant factor is growing time, namely, the longer the growing time, the higher the sweetness degree of fruit tomato. In addition, the growing time is likely to be affected by season, that is the growing time in summer is faster than in wintertime. Consequently, summer is not the best time to grow fruit tomato. Based on our study, data gathering should be continued in the same target area to conduct a more comprehensive examination. Moreover, by increasing the number of data, an estimation system to predict yields and sweetness degree of fruit tomato through machine learning can be constructed.

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