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Article

Characteristics and Trends of Strawberry Cultivars throughout the Cultivation Season in a Greenhouse

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Abstract: Each strawberry (*Fragaria* × *ananassa*) cultivar has its own growth and yield characteristics. However, the characteristics of many cultivars have not been determined at a consistent time and place, making direct comparative analysis difficult. The objective of this study was to identify characteristics and trends of five Korean strawberry cultivars in the same environment during an entire season. Therefore, environmental factors such as daily average air temperature, daily average relative humidity, daily average solar radiation, daily soil temperature, daily soil water content, daily soil electrical conductivity (EC), plant growth characteristics such as the number of leaves, plant height, leaf length, leaf width, and crown diameter, and productivity characteristics such as flowering and fruiting were measured to investigate the possible correlations of the data over one season. The vegetative growth of "Seolhyang" and "Keumsil" was greater than that of "Jukhyang" and "Maehyang". The yield of "Arihyang" was greater than that of all other cultivars. "Arihyang" also presented the greatest weight per number of fruits. Among environmental factors, higher variability in air temperature and soil water content was correlated to lower total fresh weight in the following week at different degrees for each cultivar. Among the cultivars, the time to the first flowering was delayed by about seven days when the number of leaves increased by one and was reduced by one day per 1 cm increase in plant height. The total fresh weight was enhanced up to 271 g per experimental unit, while the average number of leaves increased by one. The results indicate that the data can be used by those who need information regarding the characteristics of the strawberry cultivars through direct comparative analysis.

Keywords: *Fragaria* × *ananassa*; plant size; flowering; fresh weight; ratio of red and far-red lights

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1. Introduction

Strawberry (*Fragaria* × *ananassa*) is a high-value crop in South Korea. The production area and marketable fruit yield in 2019 were 6462 ha and 234,225 tons, respectively [1]. The yield is the 3rd largest in Asia and 7th in the world [2]. The harvest season of June-bearing strawberry cultivars is from November to May, and the winter season is dry and cold. Strawberries recover vegetative and floral vigor under a chilling effect in winter [3–5], whereas their growth is reduced as days become longer and hotter in summer than in winter [6–10]. The seasonal change also induces photoperiodic responses. For example, there is a positive correlation between the percentage of leaf area exposed to short-day photoperiods and inflorescence number per strawberry plant [11]. The photoperiodic response is quantitative (facultative), and the response curve varies for cultivars. In general, short-day genotypes initiate flowers when the photoperiod is <14 h [12]. The ratio of red and far-red light can control the growth of strawberry plants owing to the absorption of red light by leaves [13], and far-red light induces early flowering in many species [14–17].

More leaves and larger leaf size might result in more and heavier fruit. Source and sink dynamics may illustrate the relationships between the growth characteristics, such as the number of leaves, leaf size, crown diameter, and the ratio of red and far-red lights, and yield characteristics, such as flowering, the number of fruits, and fruit weight of strawberry cultivars. Giaquinta [18] reported that levels of sugar including sucrose, and activities of sucrose-metabolizing enzymes, were determined by source and sink strength.

Most strawberries in South Korea are cultivated in greenhouses. Protected cultivation has provided efficient ways to overcome climatic problems such as intense solar radiation, wind, heavy rain, frost, and hail [19]. Furthermore, the greenhouse environment can be maintained with the required water vapor, CO_2 concentration, and airflow conditions [20]. Therefore, greenhouse cultivation has facilitated crop management and monitoring, sensor installation, and data collection for a long time. For instance, Park et al. [21] determined and simulated the number of strawberry transplants without outside weather disturbance for one year. Determining plant growth and productivity in a similar manner can help our understanding of the characteristics of new June-bearing strawberry cultivars. New varieties continue to be bred in South Korea, and their characteristics are being actively studied because strawberry breeding goals in Korea include weak dormancy, vigorous growth, high yield, and fruit quality [22]. The goals will probably give a common character to the bred cultivars, but we believe that each cultivar will exhibit its own characteristics for a given environment.

Many studies have demonstrated characteristics using growth and yield data of strawberries. However, few studies have been conducted to identify trends from various cultivars cultivated in the same environment during a whole season. Thus, our hypothesis was that long-term environmental impact shows trends in the growth and yield of various strawberry cultivars. This information may provide information for improving strawberry cultivation and management in farmers' conditions for fruit production and may be used to construct a cultivation map for strawberry farmers. Strawberry farmers might thereby decide which cultivars are best for their environment on the cultivation map [23,24]. This study identified the growth and yield characteristics and the trends between the growth, flowering, fruit yield, and environmental factors for five cultivars.

2. Materials and Methods

2.1. Plant Materials and Experiment Design

Transplants of the strawberry cultivars "Keumsil", "Maehyang", and "Seollhyang" were obtained from Kyungnam Agriculture Research Station (35°12′ N 128°07′ E, elevated 20 m); "Arihyang" strawberry transplants were procured from the National Institute of Horticulture and Herbal Science (35°50′ N 127°02′ E, elevated 30 m); and "Jukhyang" was purchased from Damyang-gun transplant production in Jeollanam-do (35°18′ N 126°58′ E, elevated 45 m) (Figure 1). Twenty strawberry transplants of each cultivar were planted in two rows at intervals of 18 cm (planting density 1.6 plants/m^2) in a tunnel-type greenhouse (25 × 7 m^2) located in the Kyungpook National University experimental farm (35°53′ N 128°36′ E, elevated 30 m) from September 10 to 23, 2019. Furrow size was 12 × 24.6 m^2 twice and 12 × 22.6 m^2 once. The number of leaves, crown diameter, and plant height of strawberry transplants were 4, 5, 4, 4, and 3/plant; 12.5, 12.3, 13.7, 9.5, and 9.3 mm/plant; and 37.5, 36.5, 38.4, 42.0, and 33.6 mm/plant for "Arihyang", "Jukhyang", "Keumsil", "Maehyang", and "Seollhyang", respectively. All the strawberry transplants exhibited the 1st flower initiation. The experimental design was a completely randomized block design with five replications (20 strawberry transplants for each replication). The old and inoculated leaves were periodically removed.

"Arihyang" "Jukhyang" "Keumsil" "Maehyang" "Seolhyang"

Figure 1. The tested strawberry cultivars.

2.2. Growth Data Collection

The number of leaves, plant height, leaf length and width, and crown diameter were evaluated once every 2 weeks from the sixth day after transplanting, and the days to flowering were evaluated from 5 November 2019. The fruits were harvested from 26 November 2019 to 19 March 2020. Three plants in five replicated experiment plots (n = 15) were selected at random for data collection. The methods for measuring plant height, leaf length, and width were completed as previously reported [25].

2.3. Cultivation Environments

The greenhouse was a single span but double tunnel greenhouse in an east-to-west direction. The tunnel greenhouse was 25 × 7 m. Each greenhouse was covered with a polyolefin film. The film thickness was 0.1 mm. To prevent the dark-period air temperature from decreasing in winter, a lagging cover (complexed with aluminum, felt sheets, and cotton) was used as an insulation method from 18:00 to 08:00, and an air heater (8 kW electronic type) was automatically operated when the air temperature was <8 °C. The side window was opened during photoperiods for ventilation, and an airflow fan (diameter 600 mm) was set to operate for 25 min and to rest for 5 min. The environmental data are presented in Figure 2. The soil type was a very well-drained silt loam soil. Commercial organic matter was applied based on regional recommendations as 2000 kg per 10 are (measure of 1 are =100 square meters × 10). A nutrient solution (N-P-K-Ca-Mg-S = 16-4-8-4 me L^{-1}) was applied via irrigation once a week. A honeybee hive was located within the greenhouse to pollinate the strawberries.

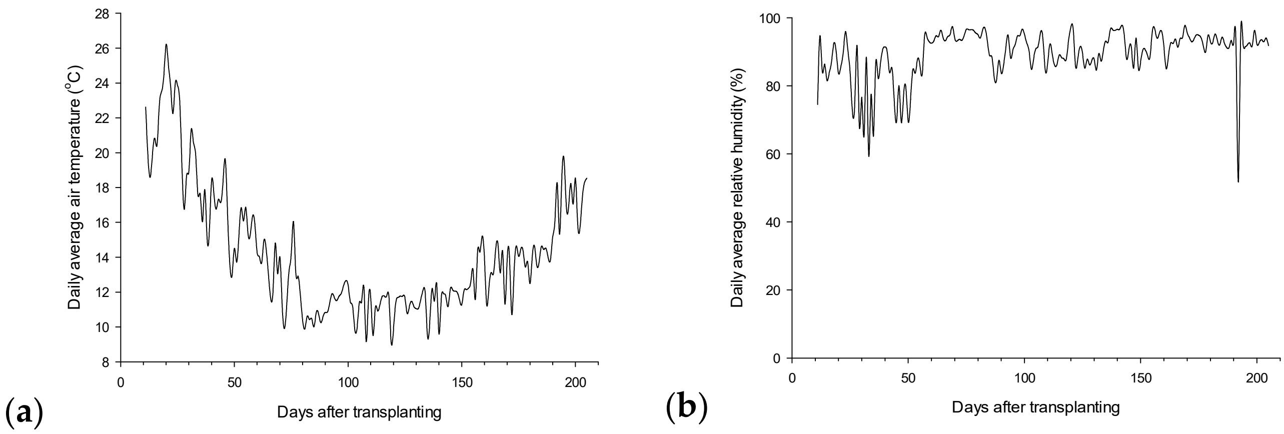

Figure 2. *Cont.*

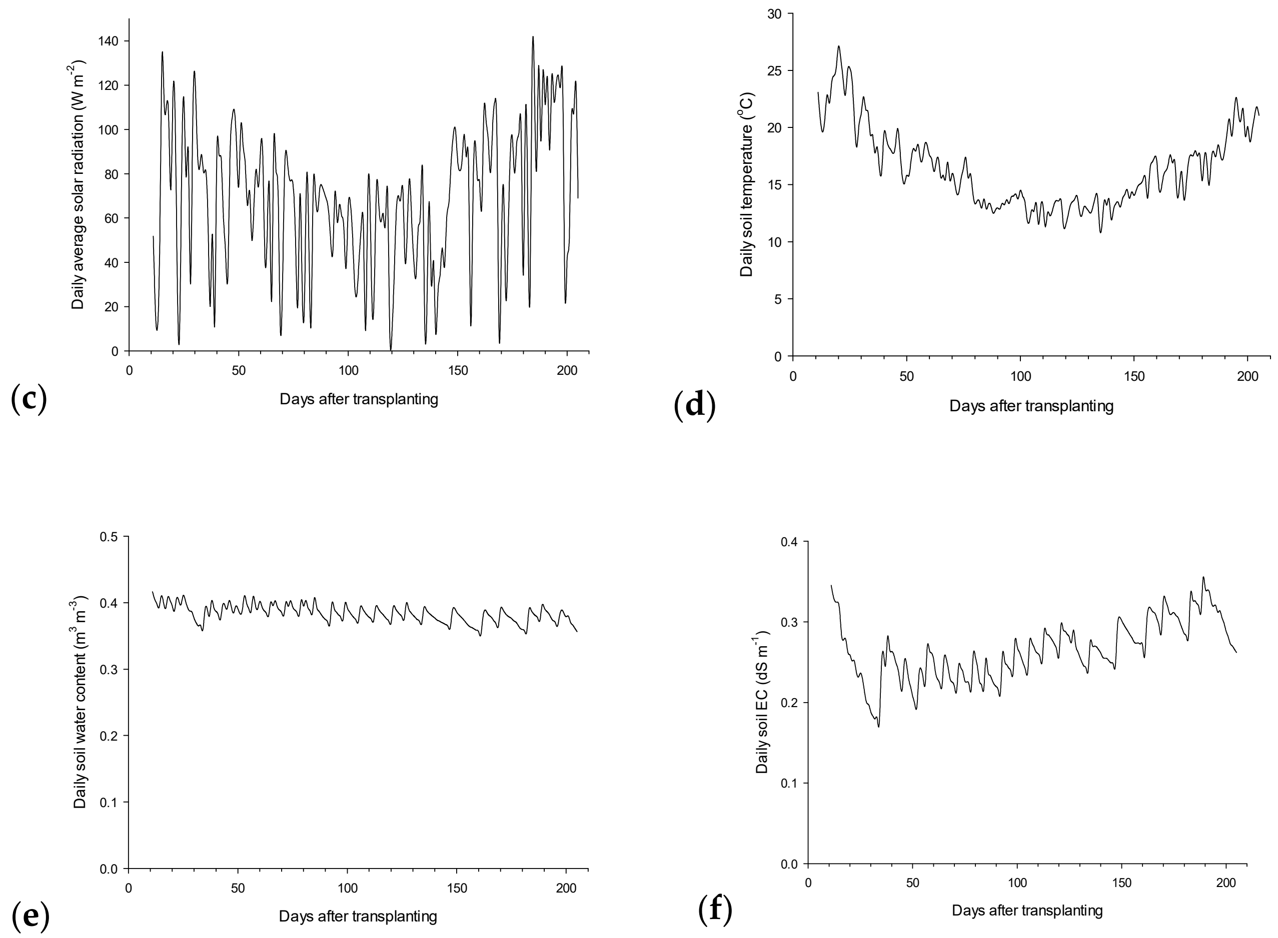

Figure 2. The environment in the greenhouse during the season. (**a**), daily average air temperature; (**b**), daily average relative humidity; (**c**), daily average solar radiation; (**d**), daily soil temperature; (**e**), daily soil water content; (**f**), daily soil electrical conductivity (EC).

2.4. Ratio of Red and Far-Red Light

The red and far-red wavelengths were measured using a spectrometer with a wavelength range of 380–780 nm (LI-180, Li-Cor, Lincoln, NE, USA). The red and far-red wavelength ranges were 620–700 nm and 700–750 nm, respectively. The red and far-red wavelengths were measured at the top of the strawberry canopy and next to the crown. To measure the red and far-red ratio of light reaching the crown, the two measurements were compared with the wavelengths detected in the shadow of the leaf.

2.5. Data Analysis

Three strawberry plants were randomly selected per replicated block and cultivar. The data were collected and recorded in Excel software (Microsoft Office 2016). We used cultivar-specific regression models to compare the growth rate of each variable (the number of leaves, plant height, leaf length, leaf width, and crown diameter) with respect to time among the five strawberry cultivars. If necessary, we used a second-order (quadratic) interaction term, which allows for a nonmonotonic trend (e.g., increasing then decreasing at a certain time point). We compared time to the first flowering among the five cultivars using analysis of variance and compared the ratio of red and far-red light using the Duncan's mean separation. We graphically compared the cumulative count and cumulative weight and then we used the second-order interaction term to compare the change of the weight per count (grams per count) with respect to time among the five cultivars. The regression modeling was conducted using the R version 4.0.2 (R Core Team, 2020). To account for correlations within experimental units, a mixed-effects model (referred to as Model 1) was used to explain the time to the first flowering by multiple explanatory variables, including the number of leaves, plant height, leaf length, leaf width, and crown diameter (measured on 14 October 2019; 34 days since transplanting). Another mixed-effects model (referred to as Model 2) was used to explain the total weight of strawberries (harvested from December to March) by the number of fruits, the number of leaves (counted on October 14), and the time to the first flowering while accounting for the cultivar.

3. Results and Discussion

3.1. Strawberry Growth Variation

A dynamic and complex set of interacting environmental factors in greenhouses, such as air temperature, photoperiod, light intensity [26], and soil temperature [27], affect the growth and yield of strawberry plants. The air temperature and photoperiod are essential for the growth and yield of strawberry cultivars because environmental factors can directly affect vegetative growth and fruit yield [28]. The two factors decreased until approximately 100 days after transplanting and then increased until the last fruit harvest (Figure 2). This trend is normal in northeast Asia, including South Korea, and may affect the environmental adaptability of the five strawberry cultivars. Plant growth should increase with time, but it sometimes decreased owing to leaf thinning (Figure 3). The number of leaves tended to increase with time at similar rates; on average, "Seolhyang" had more leaves per plant than the other four cultivars throughout the observation time. The average plant height of "Keumsil" and "Seolhyang" decreased with time, whereas the average plant height of "Arihyang", "Jukhyang", and "Maehyang" increased with time. This cultivar-specific trend was statistically significant ($p < 0.0001$). The average leaf length displayed similar cultivar-specific trends. The average leaf width of "Maehyang" was significantly shorter than that of the other four cultivars ($p = 0.0002$). Unlike the four growth variables, the average crown diameter did not follow a linear trend, and the second-order regression better described the change in crown diameter with respect to time than the first-order regression ($p = 0.0005$). In particular, the nonmonotonic trend of "Maehyang" had the most variance among the five cultivars, and the diameter of "Arihyang" tended to continually decrease with time. The differences observed while the plants were in the same environmental conditions may be more representative of the characteristics between cultivars than the other growth factors. Phytochrome, a class of photoreceptor used to detect light, depends on the ratio of red and far-red light [29]. Phytochrome A promotes flowering in Arabidopsis, whereas phytochrome B, D, and E repress it [30]. The ratio of red and far-red light in the canopy of "Maehyang" was significantly higher than that in those of the other cultivars (Table 1).

Table 1. The ratio of red and far-red light detected in the crown canopy of five strawberry cultivars during the season.

Cultivar	3 February 2020	17 February 2020	9 March 2020
"Arihyang"	0.49 a [z]	0.74 b	0.96 ab
"Jukhyang"	0.46 a	0.73 b	0.86 a
"Keumsil"	0.55 ab	0.82 bc	1.00 ab
"Maehyang"	0.70 b	0.96 c	1.12 b
"Seolhyang"	0.51 ab	0.56 a	0.91 a

[z] Mean seperation within columns by Duncan's multiple range test at a 5% significance level.

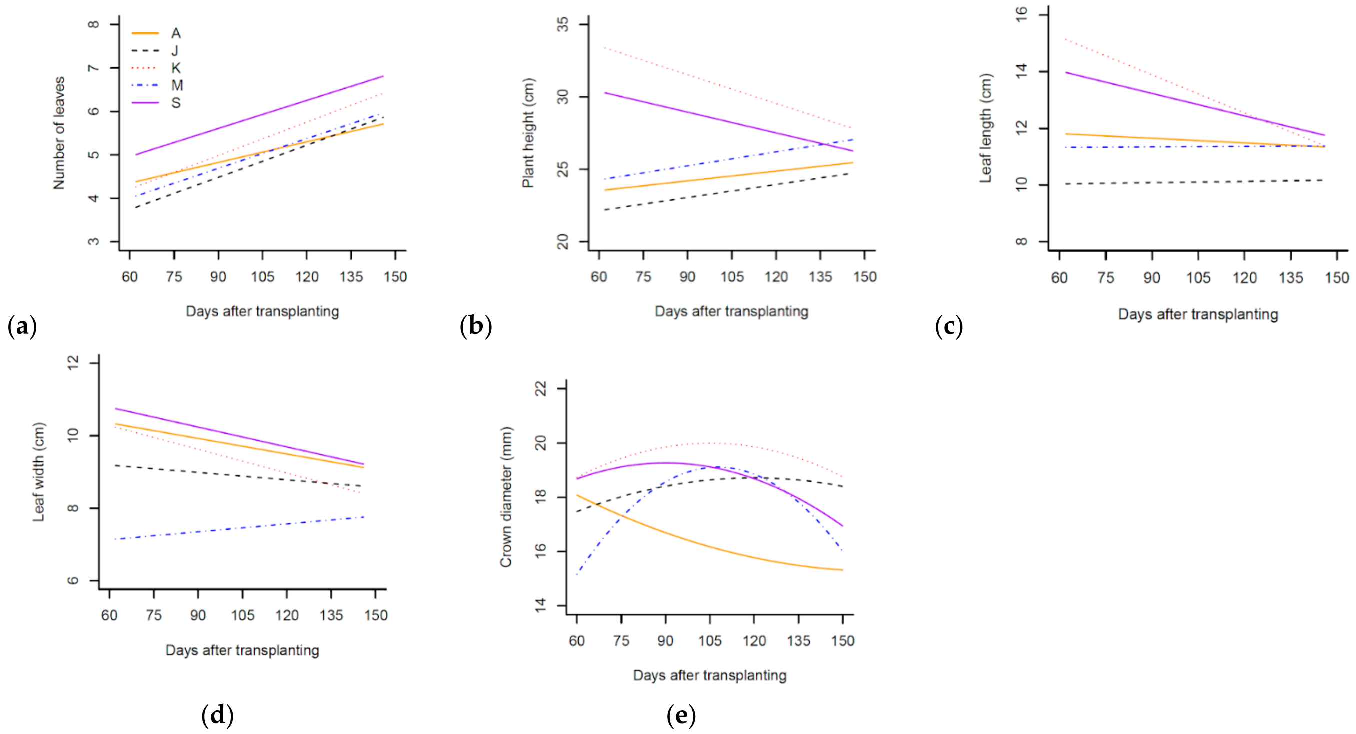

Figure 3. Growth variables (**a**): number of leaves; (**b**): plant height; (**c**): leaf length; (**d**): leaf width; (**e**): crown diameter of five strawberry cultivars during the season. A: "Arihyang," J: "Jukhyang," K: "Keumsil," M: "Maehyang," and S: "Seolhyang".

3.2. Strawberry Productivity Variation

The ANOVA test indicated statistical significance for the differences in the time for the first flowering ($p < 0.0001$). "Arihyang" tended to flower early compared with "Jukhyang", "Keumsil", and "Seolhyang" (Figure 4). The days to the first flowering of "Maehyang" were less than that of "Seolhyang", although Kim et al. [31] reported the opposite.

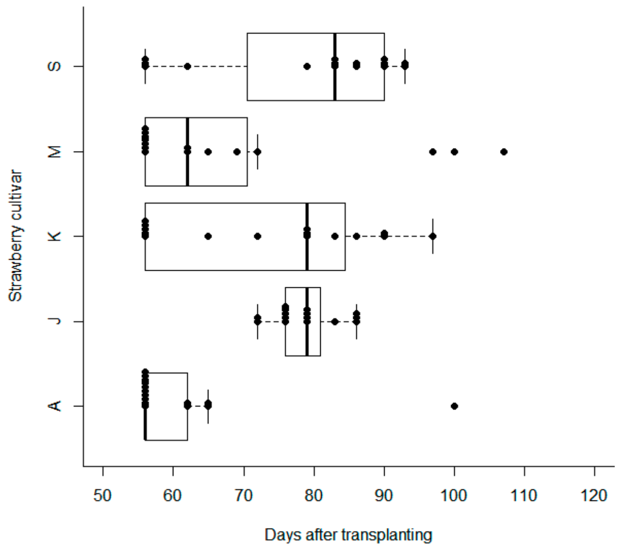

Figure 4. Days to the first flowering of the five tested strawberry cultivars during the season. A: "Arihyang", J: "Jukhyang", K: "Keumsil", M: "Maehyang", and S: "Seolhyang".

The number of fruits of "Maehyang" and fruit yield of "Arihyang" were higher than those of the other cultivars (Figure 5). The number of fruits and the ratio of red and far-red lights in the crowns of "Maehyang" presented a high positive correlation, although

Hemming et al. [32] reported a negative correlation between the two factors. This may be due to differences in characteristics of the tested cultivars and environmental factors. The number of fruits and fruit yield of "Jukhyang" was less than those of the other cultivars. "Keumsil" and "Seolhyang" had the three greatest plant height, leaf length, and crown diameter and two (the number of leaves and leaf width) growth indicators. They also produced more and heavier fruits in November and December 2019 and in February and March 2020. "Maehyang" presented higher yield than "Seolhyang" in November and December 2019, whereas Kim et al. [31] showed the opposite result in December to February for the 2009–2010 and 2010–2011 seasons. Our results indicated that when cultivar-specific characteristics were compared by taking the average within each cultivar, there was a strong correlation between the time to the first flowering and the number of fruits. The "Arihyang" cultivar, which tends to flower early, produced more fruit on average (r = 0.966). The nonlinear trends of the weight per count were substantially different among the five cultivars ($p < 0.0002$). In particular, the nonmonotonic trend (i.e., increasing then decreasing) of "Seolhyang" was different from the monotonic trend (i.e., consistently decreasing) of "Arihyang". The cultivar "Arihyang" seemed to be an outlier in the association between the ratio of red and far-red lights on 3 February 2020 and the number of fruits in March. Among the other cultivars, the correlation between the average ratio and the average number of fruits was strongly negative (r = −0.988), but the average ratio and the average number of fruits of "Arihyang" were the smallest among the five cultivars compared. On the other hand, the weight per number of fruits was the highest for "Arihyang" (nearly double compared with the other cultivars) (Figure 6). Kim et al. [33] also reported that "Arihyang" has uniformly large-sized fruit compared with "Seolhyang" and "Maehyang." In June-bearing cultivars, both temperature and photoperiod control flowering [4]. The effect of environmental factors on strawberry yield has been previously studied [34,35]. In the same environment, the cumulative fruit count and weight steadily increased regardless of the cultivar, but the difference in the weight per count clearly depended on the cultivar. Furthermore, accumulated environmental data may predict strawberry fruit yield. For example, Døving and Måge [36] predicted strawberry fruit yield using monthly air temperature and fruit yield data spanning 25–27 years. Deep learning and drone image technologies may be used to determine fruit characteristics to save cost and labor. Chen et al. [37] presented a deep learning detection system for strawberry flowers and fruits based on reconstructed high-resolution drone images.

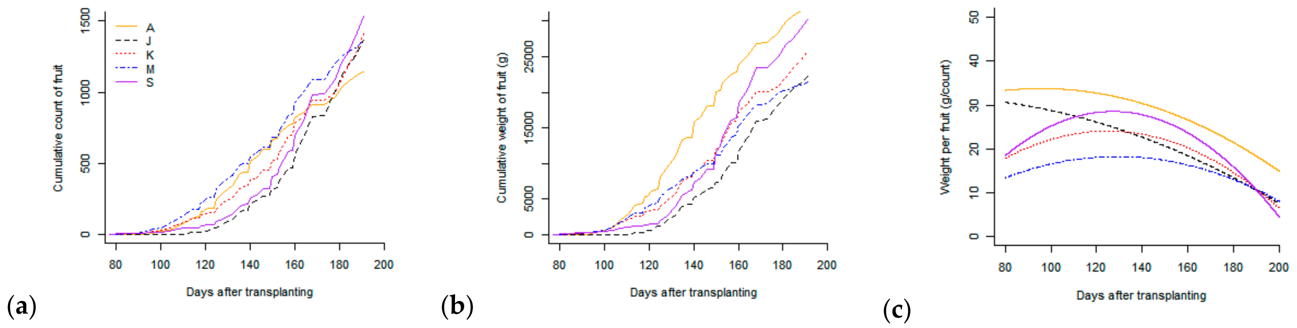

Figure 5. The cumulative count (left), cumulative weight (middle), and estimated weight per fruit by second-order regression (right) of the tested five strawberry cultivars during the season. (**a**) Cumulative count of fruit; (**b**), cumulative weight of fruit; (**c**), weight per fruit. A: "Arihyang," J: "Jukhyang," K: "Keumsil," M: "Maehyang," and S: "Seolhyang."

3.3. The Effect of Sensitivity to Environmental Variability on Strawberry Growth

Using a regression model, we compared the sensitivity of the five cultivars to environmental variability. In the regression model, the time (weeks) since transplant was adjusted, and the weekly variances of the daily average air temperature, soil water content, and average solar radiation were matched with the total fresh weight harvested in the following week. A higher variability in air temperature and soil water content was associated with lower total fresh weight in the following week at different degrees for each cultivar, with "Arihyang" being the most affected. For all five cultivars, the variability of daily solar radiation appeared uncorrelated with total fresh weight in the following week when the variances of air temperature and soil water content were included in the regression model. All estimated regression parameters and *p*-values are provided in Table 2.

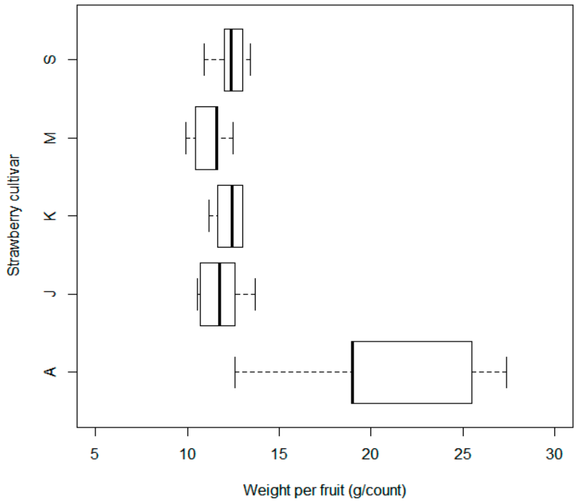

Figure 6. The weight per number of fruits among the tested five strawberry cultivars during the season. A: "Arihyang", J: "Jukhyang", K: "Keumsil", M: "Maehyang", and S: "Seolhyang".

Table 2. Estimated regression parameters, standard errors (SE), test statistics (Z), and *p*-values for the cultivar-specific relationships between the variability of environmental factors (daily air temperature, daily soil water content, and daily solar radiation) and fresh weight harvested in the following week (adjusting for weeks since transplanting).

Cultivar		Estimate	SE	Z	*p*-Value
Arihyang	Intercept	865.4300	98.0682	8.8248	<0.0001
	Weeks since transplanting	18.1823	0.9510	19.1192	<0.0001
	Variance of daily air temperature	−150.3738	28.0690	−5.3573	<0.0001
	Variance of daily soil water content	−78,412.9611	8666.3642	−9.0480	<0.0001
	Variance of daily solar radiation	−1.3067	1.7582	−0.7432	0.4573
Jukhyang	Intercept	865.4300	98.0682	8.8248	<0.0001
	Weeks since transplanting	−598.6404	136.5496	−4.3840	<0.0001
	Variance of daily air temperature	−28.3017	28.0690	−1.0083	0.3133
	Variance of daily soil water content	−40,960.7991	8666.3642	−4.7264	<0.0001
	Variance of daily solar radiation	0.6161	1.7582	0.3504	0.7260
Keumsil	Intercept	865.4300	98.0682	8.8248	<0.0001
	Weeks since transplanting	−598.6404	136.5496	−4.3840	<0.0001
	Variance of daily air temperature	−59.5143	28.0690	−2.1203	0.0340
	Variance of daily soil water content	−49,156.6153	8666.3642	−5.6721	<0.0001
	Variance of daily solar radiation	−0.5555	1.7582	−0.3160	0.7520
Maehyang	Intercept	865.4300	98.0682	8.8248	<0.0001
	Weeks since transplanting	−598.6404	136.5496	−4.3840	<0.0001
	Variance of daily air temperature	−20.0825	28.0690	−0.7155	0.4743
	Variance of daily soil water content	−46,499.2503	8666.3642	−5.3655	<0.0001
	Variance of daily solar radiation	−2.2026	1.7582	−1.2528	0.2103
Seolhyang	Intercept	865.4300	98.0682	8.8248	<0.0001
	Weeks since transplanting	−598.6404	136.5496	−4.3840	<0.0001
	Variance of daily air temperature	−89.4155	28.0690	−3.1856	0.0014
	Variance of daily soil water content	−54,711.1508	8666.3642	−6.3130	<0.0001
	Variance of daily solar radiation	−0.7698	1.7582	−0.4378	0.6615

3.4. The Correlation between Strawberry Growth and the First Flowering

The results from the mixed-effects model (Model 1) are summarized in Table 3. According to the model estimates, the expected time to the first flowering was longer by about 7 days when the number of leaves increased by one ($p < 0.002$) and shorter by 1 day per one cm increase in plant height ($p < 0.015$). These results are consistent with Riihimäki and Savolainen's [38] report that four *Arabidopsis lyrata* displayed a positive correlation between the number of leaves and days to flowering. The other variables (leaf length, leaf width, and crown diameter) did not further explain the time to the first flowering. When we further accounted for the cultivar, the estimates did not change substantially, and "Arihyang" tended to flower 20, 21, 12, and 22 days earlier than "Jukhyang", "Keumsil", "Maehyang", and "Seolhyang", respectively.

Table 3. Estimated regression parameters, standard errors (SE), test statistics (T), and *p*-values of the mixed-effects model (Model 1).

	Estimate	SE	T	*p*-Value
Intercept	55.1701	16.2989	3.3849	0.0016
Number of leaves	6.6342	2.1027	3.2027	0.0021
Plant height (cm)	−1.0537	0.4168	−2.5281	0.0150
Leaf length (cm)	3.1171	1.8725	1.6647	0.1021
Leaf width (cm)	−0.8609	2.0631	−0.4173	0.6781
Crown diameter (mm)	−0.6308	0.5475	−1.1522	0.2544

3.5. The Effect of the Number of Leaves and Fruits on Fruit Fresh Weight

The strawberry fruit weighed about 20 g on average (Table 4). When we adjusted the cultivar and the number of fruits per experimental unit, the total expected weight was 271 g higher per experimental unit when the average number of leaves (measured in that experimental unit on October 14) was higher by one ($p < 0.045$). The expected fruit weight was 21 g lower per experimental unit when the average number of days to the first flowering (measured in that experimental unit) was shorter by 1 day ($p < 0.028$). In general, the leaves of plants produce photosynthetic products; the more leaves there are, the more sugar is available for the development of bigger and heavier fruit. The total fruit yield per strawberry plant can be reduced by partial leaf removal [39] because removal of source organs reduced photoassimilate production [40]. Lacey [41] reported that the correlation coefficients between the number of leaves and the total fruit weight of strawberry plants from May to July and September to April were 0.72 and 0.50 ($p < 0.01$), respectively.

Table 4. Estimated regression parameters of the mixed-effects model (Model 2).

	Estimate	SE	T	*p*-Value
Intercept	30.3904	1019.4290	0.0298	0.9765
Number of fruits	19.7760	1.4561	13.5815	<0.0001
Number of leaves	270.6740	126.7974	2.1347	0.0451
Days to flower	−21.1485	8.8336	−2.3941	0.0277

4. Conclusions

In summary, the characteristics of each cultivar were revealed. Correlations between the ratio of red and far-red light in the canopy and the number of fruits, the days to the first flowering and the number of leaves, the days to the first flowering and plant height, the number of leaves and fruit fresh weight, the days to the first flowering, and fruit fresh weight were found. Furthermore, one cultivar ("Arihyang") was more sensitive to the variability in air temperature and soil water content, which resulted in lower total fresh weight in the following week. This approach and the information that results may help farmers decide which cultivars to grow depending on their ability to control these factors. Even though this study was designed to be close to the typical farm environmental conditions, there could be unintended sources of bias and variations in this study, so data collection will be continued to replicate the results observed in this study. Future research should focus on the characteristics of each cultivar by continuous correlation analysis from transplant to harvest.

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