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Sabine Wittmann*, Ivonne Wittmann, Heike Mempel

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Hochschule Weihenstephan-Triesdorf, Institute of Horticulture,
Applied Science Centre for Smart Indoor Farming,
Am Staudengarten 10, 85354 Freising, Germany;
sabine.wittmann@tum.de, ivonne.wittmann@hswt.de, heike.mempel@hswt.de

* Correspondence: sabine.wittmann@tum.de

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Sabine Wittmann, Ivonne Wittmann, Heike Mempel

University of Applied Sciences Weihenstephan-Triesdorf,
Institute of Horticulture, Applied Science Centre for Smart Indoor Farming, Germany

Abstract

Vertical indoor farming (VIF) optimizes yields and quality but faces high energy demands. One key objective of vertical indoor farming is to achieve high yields. For strawberries, a high-value crop, pollination is essential to reach high yields. However, the reaction of bumblebees to the sole artificial light of a VIF and the effect on yield are not yet known. To address this, bumblebees (*Bombus* spp.) were studied in a multi-layer VIF container system with and without additional UV (365 nm) light to evaluate the effect on flight activity and strawberry yield. The results indicated an estimated annual yield of 14 kg FM m^{-2} a^{-1} for bumblebee pollination, representing a two-fold increase over wind pollination. The additional UV light increased the flight activity of bumblebees, but had no effect on yield and ultimately reduced energy efficiency. Based on this experiment, bumblebees can be used for pollination in VIF strawberry cultivation without additional UV light to increase fruit yield.

1. Introduction

Innovative approaches such as the research project CUBESCircle are paving the way for sustainable and efficient food production systems. By the integration of fish, plants, and insects as a synergistic environment enhanced productivity is reached, while contributing to a more sustainable agricultural paradigm. Within the CUBESCircle framework, RemoteCUBE serves as a Vertical Indoor Farm (VIF) designed for year-round plant cultivation with minimal resource consumption. Integrated alongside a high-tech greenhouse, RemoteCUBE provides a comprehensive solution for plant production. Among the various crops suitable for vertical indoor farming, strawberries have been identified as a high-value crop (van Delden et al. 2021). The economic viability of VIF hinges on the cultivation of such high-value crops, which can provide significant returns on investment. Several studies have highlighted the potential of strawberries for indoor multilayer production (Yoshida et al. 2016; Alvarado-Camarillo et al. 2024). These studies suggest that strawberries can thrive in controlled environments, producing high yields and high fruit quality. One key objective of vertical indoor farm is to achieve high yields, which necessitates effective pollination strategies for strawberries. Pollination is crucial for the yield, fruit size, and shelf life of strawberries in greenhouse production (Klatt et al. 2014; Trillo et al. 2018). Effective pollination can significantly enhance the productivity and quality of strawberry crops, making strawberry a relevant crop for research and development in VIF systems regarding the effect of pollination. Nevertheless, research on the reaction of pollinators under artificial lighting conditions remains limited (Lazzarin et al. 2021; de Vries et al. 2020) and is not available for VIF. Known issues in greenhouses with artificial light include suboptimal growth and development, which can affect overall crop performance (Maebe et al. 2013). Bumblebees are sensitive to UV (328 nm), blue (428 nm), and green (536 nm) and may respond to additional UV exposure (Peitsch et al. 1992; Chittka et al. 2013). This sensitivity to specific light wavelengths suggests that optimizing light conditions could improve bumblebee activity and, consequently, pollination efficiency. Addressing this question is critical for advancing the understanding of how to optimize VIF practices for strawberries and potentially other high-value insect pollinated crops. Therefore, the aim of this paper was to evaluate if the flight activity of bumblebees improves under additional UV light, leading to increased yields, crop quality, and efficiency through enhanced pollination and UV light exposure.

2. Data, Methods and Approach

The experiment was conducted in a container VIF system equipped with six shelving racks as a multilayer cultivation system (4 layers per cultivation area, each 1.5 x 0.6 x 0.42 m), placed along the walls with a central walkway. LEDs with a white spectrum were used as the control, and additional UV-A (365 nm) as the comparison variant (Tab. 1).

Table 1: Light treatment used (DLI = daily light integral; PPFD = Photosynthetic Photon Flux Density)

Light treatment	Light spectra UV | B | G | R | FR (%)[a]	PPFD/PFD[b] (µmol m^{-2} s^{-1})	Photoperiod (h) (9 am – 3 am)	DLI (mol m^{-2} d^{-1})
White	0 | 18 | 38 | 39 | 6	320 ± 50 | 341 ± 50	18	20.7 ± 3.2
White+UV	2 | 17 | 37 | 38 | 6	320 ± 50 | 349 ± 50	18	20.7 ± 3.2

[a] UV (300-400 nm) | Blue (401–500 nm) | Green „G" (501–600 nm) | Red „R" (601–700 nm) | far Red „FR" (701–800 nm)
[b] PPFD (400-700 nm); PFD (300-800 nm)

The two light variants were installed on either side of the central walkway and separated by a dark curtain, which hung freely 30 cm at the top and bottom to allow air movement and bumblebee flight. Strawberry plants (*Fragaria x ananassa*, cultivar 'Elsanta') were selected as the representative fruit crop due to their popularity in German cultivation and therefore higher data availability. The plants were cultivated in deep-water culture in euro-stacking boxes (0.4 x 0.3 x 0.12 m, AUER GmbH, Germany), each containing six plants in net pots (plant density: 25 plants m^{-2}). Six boxes were randomly placed in each light treatment respectively. For pollination, two small bumblebee colonies specifically for 1-25 m^2 (*Bombus terrestris*, Natupol Seeds, Koppert, Germany) were placed in the system above the cultivation layers and LEDs, with one box on each side of the central walkway. Bumblebee flight activity was monitored using time-lapse cameras installed in one layer per light treatment. The flight activity of the bumblebees was observed daily over a period of 48 days. Observations were made at four fixed times: 3, 7, 11, and 15 h after 9 am, when lights went on (Tab. 1). Each observation lasted 4 minutes, with manual counting of flight movements that lasted longer than 3 seconds on one level. As control regarding pollination the flowers of three plants per box were covered with perforated bags (wind pollination only) while the flowers of the remaining three plants per box remained accessible for bumblebee pollination. The strawberry plants (A++ grade, Frigo plants, KRAEGE Beerenpflanzen, Germany) were supplied with desalinated water for the first two weeks. Subsequently, a nutrient solution was applied, consisting of major nutrients (mmol l^{-1}): 10.0 N (NO_3), 1.2 P, 3.0 K, 2.0 Mg, 3.0 Ca and minor nutrients (µmol l^{-1}): 25.0 Fe, 8.0 Mn, 25.0 B, 0.5 Mo, 0.5 Cu, and

0.5 Zn. The nutrient solution was manually adjusted three times per week to maintain an EC value of 1.6 ± 0.3 mS cm^{-1}, a pH of 6.0 ± 0.5, and a water level in the box of 6 ± 2 cm. Cultivation conditions were controlled at set points for temperature (20/18 °C), humidity (60% rH), and CO_2 concentration (1000 ppm). Fully mature fruits were harvested three times per week, with the fresh mass per fruit recorded and non-marketable fruits excluded from further analysis. Organoleptic quality parameters such as firmness (measured with a penetrometer, 3.5 mm FirmTech FT7, UP, Germany) and sugar content (measured with a handheld refractometer, Hi 96822, Hanna Instruments, Germany) were assessed weekly on a sample of fruits. The total yield of fresh strawberry mass per plant was multiplied by the planting density and the cultivation time to calculate the potential annual yield in kg FM m^{-2} a^{-1}. The calculation of the energy use efficiency of the lighting was based on the measured and summed power consumption of the LEDs per light treatment over the cultivation time (White 237 kWh m^{-2}; White+UV 359 kWh m^{-2}), expressed as grams of fresh mass per MJ. The statistics were calculated using a two-factor ANOVA (Pollination x Light). Data were averaged at box level (3 plants per box; n = 6 per treatment). Assumptions were checked (Shapiro–Wilk for normality, Levene for homogeneity), and variables were transformed if required. Effects of Light and Pollination were tested using a two-factor ANOVA with Tukey HSD for post-hoc comparisons ($\alpha = 0.05$).

3. Results and Discussion

Investigating the flight of bumblebees in VIF revealed for both light treatments a noticeable difference in flight activity regarding day and daytime. In our experiment, flight activity remained constant for 8-10 days, with approximately 8 observed bumblebees per day under White light and 18 under White+UV light conditions (Fig. 1A). After this period, a clear

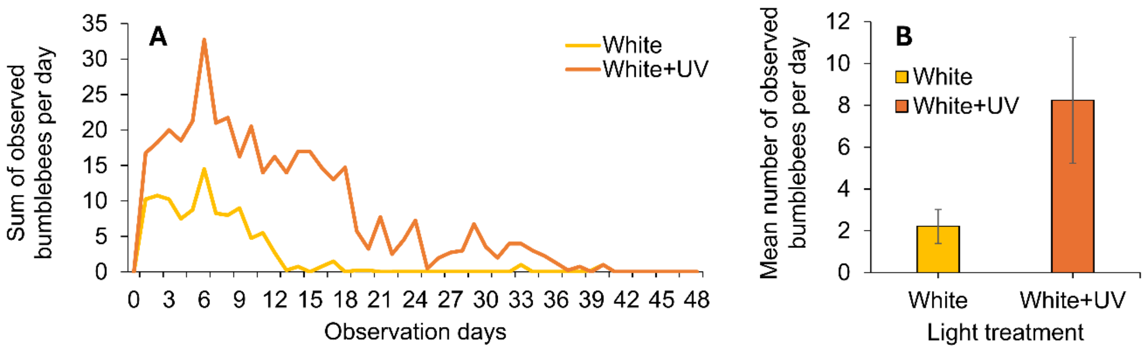

Figure 1: Daily flight activity of bumblebees was observed for 48 d for 4-min. each at 3, 7, 11, and 15 h after lights on in a VIF. (A) shows the total daily observations, and (B) the mean observations per light treatment over the whole period.

decline was observed in both light treatments. In the treatment White the observations reduced to about 1 per day after 13 days, while White+UV conditions reduced after 39 days (Fig. 1A). To ensure continuous pollination, a new bumblebee colony is usually introduced at intervals of 4-6 weeks. Since our colony had no queen and only a small amount of brood, a general reduction in activity was therefore expected. The observed decline was also reported in the literature for a greenhouse with artificial light conditions, which reported a decline within the first 4-6 days to ¼ of the workers (Blacquière et al. 2007) and in greenhouse conditions with global radiation, who also reported a reduction of the bumblebee density during the first 14 days (Lefebvre and Pierre 2006). Notably, the highest flight activity in both treatments occurred immediately after the lights were turned on, analogous to morning (Fig. 2B). These observations are in line with earlier research, which reported the highest flight activity of bumblebees during mornings (Lefebvre and Pierre 2006; Kwon and Saeed 2003; Meisels and Chiasson 1997). Our findings on the flight behavior of bumblebees in VIF, including hive duration and daily activity, indicate a general suitability as pollinators in VIF. Together with these behavioral observations, several methodological considerations need to be acknowledged. Our experiment followed a split-plot structure with Light as the whole-plot factor and Pollination as the subplot factor, with Box as a random effect. Accordingly, a linear mixed-effects framework would be more appropriate than a fixed-effects two-way ANOVA to account for the correct error strata. For flight-activity counts, a generalized mixed-effects model with an appropriate link function and treatment of overdispersion and repeated measures is recommended. Importantly, in this study each light treatment was paired with a single colony, which confounds the light effect with colony identity, future work should include multiple colonies per light treatment or a colony crossover.

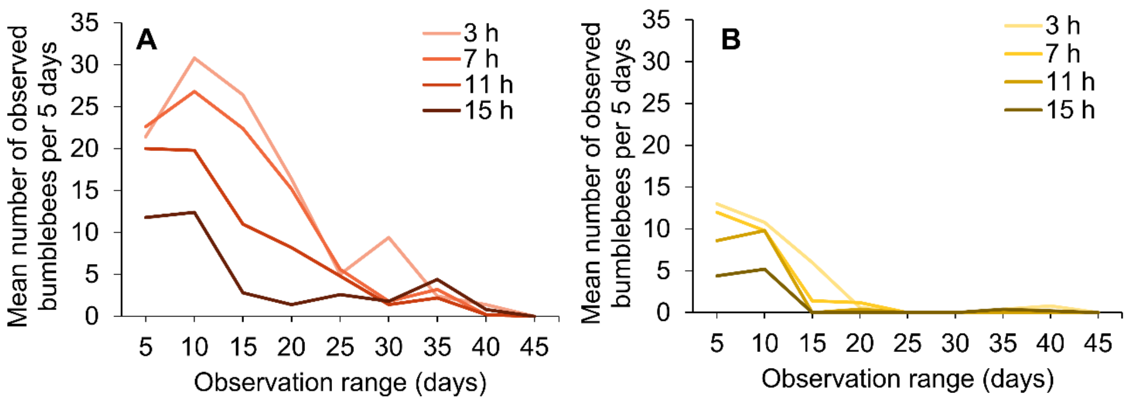

Figure 2: Daily flight activity of bumblebees observed for 48 d at 3, 7, 11, and 15 h after lights on in a VIF. Each 4-min obs. involved manual counting of flight movements >3 s. The mean obs. per 5 d at each time point are shown for (A) White+UV and (B) White.

Understanding the impact of flower accessibility on bumblebee pollination can provide valuable insights into optimizing strawberry production. Bumblebee pollination significantly increased the number of fruits, fruit yield per plant, and fruit diameter compared to wind pollination alone (Tab. 2). These findings are consistent with the literature, which reports improvements in strawberry yield, fruit size, and quality due to enhanced pollination (Klatt et al. 2014; Trillo et al. 2018). Our experiment observed increased flight activity of bumblebees in the light treatment with additional UV (Fig. 1B), aligning with previous research that also noted heightened bumblebee activity under UV conditions (Morandin et al. 2001; Costa et al. 2002). However, the additional UV light did not impact fruit number, fruit weight, or fruit diameter (Tab. 2). It has been shown that UV light does not always correlate with improved foraging efficiencies (Morandin et al. 2002). Some researchers suggest that bumblebees might be attracted to UV conditions, potentially disrupting efficient foraging (Morandin et al. 2001; Morandin 2002). Additionally, another study found that the absence of UV light does not impair bumblebees' ability to locate flowers effectively (Dyer and Chittka 2004). In conclusion, the absence of UV light did not seem to reduce the ability of bumblebees to locate flowers in VIF.

Table 2: Fruit characteristics of harvested strawberries in VIF: Means of 6 replicates (3 plants each) with SD are shown. Letters indicate significant differences between pollination and light treatments (Tukey's test)

Main effect	fruits per plant	Fruit weight (gFW plant^{-1})	fruit diameter (cm)	Firmness (g mm^{-1})	TSS (°brix)	TSS:TA
Wind	27.3 ± 7.3 b	61.2 ± 17.0 b	2.5 ± 0.4 b	155.4 ± 37.7 a	8.3 ± 1.5 a	0.9 ± 0.3 a
Bumblebee	43.0 ± 9.6 a	117.9 ± 19.6 a	2.5 ± 0.4 a	166.6 ± 37.7 a	7.4 ± 0.9 b	0.8 ± 0.1 a
White	33.6 ± 12.4 A	84.2 ± 33.0 A	2.5 ± 0.4 A	168.6 ± 33.6 A	8.1 ± 1.5 A	0.9 ± 0.3 A
White+UV	36.7 ± 10.6 A	94.9 ± 33.7 A	2.5 ± 0.4 A	156.7 ± 40.7 A	7.5 ± 0.9 B	0.8 ± 0.1 A
Pollination	*p = 0.002*	*p = 0.006*	*p = 0.018*	*ns*	*p = 0.008*	*ns*
Light treatment	*ns*	*ns*	*ns*	*ns*	*p = 0.034*	*ns*
Pol. x Light	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Our results suggest an annual yield of up to 13.9 ± 2.3 kg FM m^{-2} (White+UV with bumblebees), assuming 4.5 cultivation cycles per year in the VIF (Fig. 3A). The yield of one cultivation cycle was 3.1 kg FM m^{-2}, which is comparable to reported production ranges of 0.48-3.4 kg FM m^{-2} in open field production (Lafer 2016; Stadler 2016). This indicates that while yields are within expected ranges, further optimizations could be expected, enhancing the productivity in VIF further. Furthermore, energy efficiency was significantly reduced in the pollinated variant due to the use of UV light (Fig. 3B), both because of the increased power consumption of the UV lamps and because the increased flight activity of the bumblebees did not translate into higher yields.

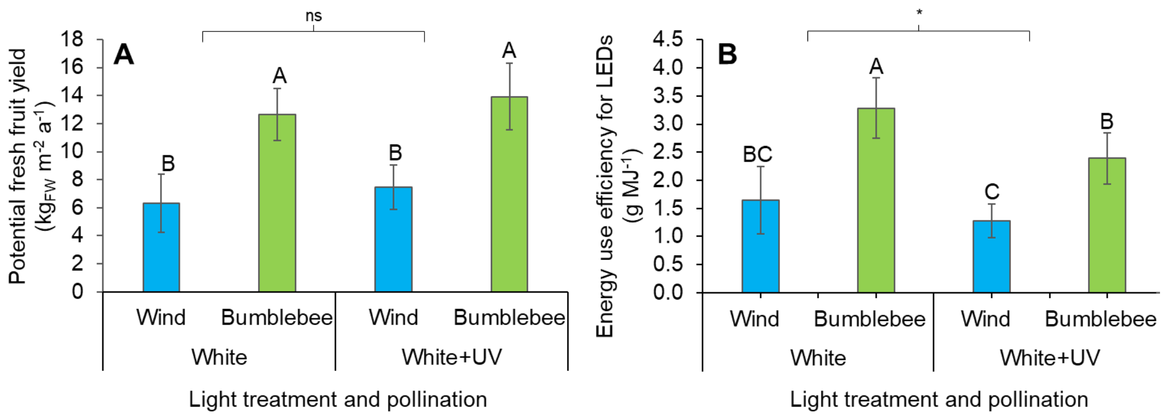

Figure 3: In (A) the potential fresh fruit yield of strawberries in VIF with/without pollination, and (B) EUE for LEDs is shown. Letters denote significant differences between pollination and light treatments (Tukey's test). Stars indicate significant light treatment effects.

4. Conclusions

This study assessed the impact of UV light on bumblebee activity and strawberry yield in VIF. While UV light increased bumblebee flight activity, it did not improve yields. With up to 14 kg FM m^{-2} annually across 4.5 cultivation cycles, VIF achieves productivity comparable to greenhouses. However, the high energy demand of UV light challenges its viability for sustainable farming. These findings suggest that effective pollination alone can enhance strawberry yields in VIF, without requiring additional UV light.

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Literature

Alvarado-Camarillo D, Valdez-Aguilar LA, Cartmill DL, Cartmill AD (2024) Strawberry Grown in an Indoor Vertical Farm Responds to Increased Photosynthetic Photon Flux Density When Calcium Is Supplied at Higher Concentrations. HortScience 59(12): 1806-1814, DOI: 10.21273/HORTSCI18230-24

Blacquière T, Cornelissen B, Donders J (2007) Bumble bee colony decline in greenhouses with supplemental lighting. Proceeding of the section Experimental and Applied Entomology of the Netherlands Entomogical Society, Vol. 18: 71-77

Chittka L, Stelzer RJ, Stanewsky R (2013). Daily changes in ultraviolet light levels can synchronize the circadian clock of bumblebees (Bombus terrestris). Chronobiology International 30(4): 434-442, DOI: 10.3109/07420528.2012.741168

Costa HS, Robb KL, Wilen CA (2002) Field trials measuring the effects of ultraviolet-absorbing greenhouse plastic films on insect populations. Journal of Economic Entomology 95(1): 113-120, DOI: 10.1603/0022-0493-95.1.113

de Vries LJ, van Langevelde F, van Dooremalen C, Kornegoor IG, Lankheet MJ, van Leeuwen JL, Naguib M, Muijres FT (2020) Bumblebees land remarkably well in red-blue greenhouse LED light conditions. Biology Open 9(6): bio046730, DOI:10.1242/bio.046730

Dyer AG, Chittka L (2004) Bumblebee search time without ultraviolet light. Journal of Experimental Biology 207(10): 1683-1688, DOI: 10.1242/jeb.00941

Klatt BK, Holzschuh A, Westphal C, Clough Y, Smit I, Pawelzik E, Tscharntke T (2014) Bee pollination improves crop quality, shelf life and commercial value. Proceedings of the Royal Society B: Biological Sciences 281(1775): 20132440, DOI: 10.1098/rspb.2013.2440

Kwon YJ, Saeed S (2003) Effect of temperature on the foraging activity of Bombus terrestris L. (Hymenoptera: Apidae) on greenhouse hot pepper (Capsicum annuum L.). Applied Entomology and Zoology 38(3): 275-280, DOI: 10.1303/aez.2003.275

Lafer G (2016) Prüfung neuer remontierender Erdbeersorten im Folientunnel, Ed: Amt der Steiermärkischen Landesregierung, Abteilung 10 Land- und Forstwirtschaft, Versuchsstation Obst- und Weinbau Haidegg, Online available at: https://www.agrar.steiermark.at/cms/dokumente/12732975_13888112/628a6954/2016-04%20Gesamt.pdf. (Accessed: 18 January 2023)

Lazzarin M, Meisenburg M, Meijer D, Van Ieperen W, Marcelis LFM, Kappers IF, van der Krol AR, van Loon JJA, Dicke M (2021) LEDs make it resilient: effects on plant growth and defense. Trends in Plant Science 26(5): 496-508

Lefebvre, D, Pierre J (2006) Spatial distribution of bumblebees foraging on two cultivars of tomato in a commercial greenhouse. Journal of economic entomology 99(5): 1571-1578, DOI: 10.1093/jee/99.5.1571

Maebe K, Meeus I, Smagghe G (2013) Recruitment to forage of bumblebees in artificial low light is less impaired in light sensitive colonies and not only determined by external morphological parameters. Journal of Insect Physiology 59(9): 913-918, DOI: 10.1016/j.jinsphys.2013.06.012

Meisels S, Chiasson H (1997) Effectiveness of Bombus impatiens Cr. as pollinators of greenhouse sweet peppers (Capsicum annuum L.). Acta Hort 437: 425-429, DOI: 10.17660/ActaHortic.1997.437.56

Morandin LA, Laverty TM, Kevan PG (2001) Bumble bee (Hymenoptera: Apidae) activity and pollination levels in commercials tomato greenhouses. J. Econ. Entomol 94(2): 462-467, DOI: 10.1603/0022-0493-94.2.462

Morandin LA, Laverty TM, Gegar RJ, Kevan PG (2002) Effect of greenhouse polyethelene covering on activity level and photoresponse of bumble bees. Can. Entomol 134: 539-549, DOI: 10.4039/Ent134539-4

Peitsch D, Fietz A, Hertel H, de Souza J, Ventura DF, Menzel R (1992) The spectral input systems of hymenopteran insects and their receptor-based colour vision. Journal of Comparative Physiology A, 170: 23-40, DOI: 10.1007/BF00190398

Stadler, P. (2016) ‘Substraterdbeeren Versuchsbericht 2016’. Online available at: https://arenenberg.tg.ch/public/upload/assets/40420/16_Versuchsbericht_Substraterdbeeren.pdf?fp=1 (Accessed: 18 January 2023).

Trillo A, Herrera JM, Vilà M (2018) Managed bumble bees increase flower visitation but not fruit weight in polytunnel strawberry crop. Basic and Applied Ecology 30: 32-40, DOI: 10.1016/j.baae.2018.05.008

van Delden SH, SharathKumar M, Butturini M, Graamans LJA, Heuvelink E, Kacira M, Kaiser E, Klamer RS, Klerkx L, Kootstra G, Loeber A, Schouten RE, Stanghellini C, van Ieperen W, Verdonk JC, Vialet-Chabrand S, Woltering EJ, van de Zedde R, Zhang Y, Marcelis LFM (2021) Current status and future challenges in implementing and upscaling vertical farming systems, Nature Food 2 (12): 944-956, DOI: 10.1038/s43016-021-00402-w

Yoshida H, Mizuta D, Fukuda N, Hikosaka S, Goto E (2016) Effects of varying light quality from single-peak blue and red light-emitting diodes during nursery period on flowering, photosynthesis, growth, and fruit yield of everbearing strawberry. Plant Biotechnology 33 (4): 267-276, DOI: 10.5511/plantbiotechnology.16.0216a