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Advanced strawberry farming: effect of UV light and fruiting characteristics on resource efficiency in Vertical Indoor Farming

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Summary

Vertical Indoor Farming (VIF) offers a potential for high-quality strawberry production, but resource efficiency data still need to be provided. Three strawberry cultivars with different fruiting characteristics, one Ever-bearing cultivar and two June-bearing (high-yielding and an old, traditional) cultivars, and two light treatments were investigated: artificial white LED light with an additional 2% UV_A (365 nm) and white LED light alone. The Ever-bearing cultivar demonstrated significantly higher efficiencies for surface use efficiency (SUE) of 15.2 kg fresh weight m^{-2} a^{-1}, water use efficiency (WUE) of 291 g fresh weight $l^{-1,}$ and energy use efficiency (EUE) of 10.6 g fresh weight kWh^{-1}, due to a high harvest index of up to 0.8 and a low proportion of non-marketable fruit. However, the total energy demand of a container VIF is high, with 4.4-6.4 kWh m^{-2} d^{-1}. Additional UV_A radiation did not significantly alter the Ever-bearing cultivar's performance. At the same time, multiple harvests and a low proportion of non-marketable fruits led to a higher cumulative yield and increased efficiency, making it a promising choice for strawberry cultivation in VIF.

Keywords: Energy efficiencies, multilayer cultivation system, artificial LED light, UVA, Ever-bearing cultivars

Introduction

Consumer demand for healthy, locally sourced food with a minimal environmental footprint highlights the need for sustainable and efficient agricultural solutions. Vertical Indoor Farming (VIF) represents a promising component in addressing these challenges with its technologically advanced approach. VIF uses multilayer soilless cultivation with artificial Light Emitting Diode (LED) lighting for high-density indoor crop production, enabling consistent, high-quality, year-round yields regardless of location, climate, or soil fertility (VAN DELDEN et al., 2021). However, VIF operations require high energy consumption for artificial lighting and system cooling, significantly impacting production costs. Improving yield in VIF while maintaining or reducing energy consumption, especially in terms of light, can consequently reduce total energy consumption (KOBAYASHI et al., 2022; LUBNA et al., 2022). Efficiencies are expressed in terms of marketable biomass (fresh or dry weight (g_{FW} or g_{DW})) per consumed resource. Currently, commercial VIF primarily focuses on cultivating leafy greens due to their small size, high harvest indices, short growth cycles, and low light energy requirements, all contributing to high resource efficiencies and productivity (O'SULLIVAN et al., 2019; VAN DELDEN et al., 2021). Studies in VIF report Energy Use Efficiencies for the LEDs (EUE_{light}) ranging from 40.9-110.0 g_{FW} kWh^{-1} for lettuce and 45.0 g_{FW} kWh^{-1} for basil (PENNISI et al., 2020). Data on the total VIF (EUE_{total}) and the Water Use Efficiency (WUE) were documented for lettuce (48.1-142.9 g_{FW} kWh^{-1}; 60 g_{FW} l^{-1} (AVGOUSTAKI and XYDIS, 2021; BLOM et al., 2022; KOBAYASHI et al., 2022) and basil (38 g_{FW} l^{-1}) (PENNISI et al., 2020; KOBAYASHI et al., 2022). However, leafy greens generally offer lower economic and nutritional value. Therefore, incorporating more profitable crops like fruiting vegetables or berries into VIF is essential (KWON, 2023; O'SULLIVAN et al., 2019). Efficiency data for these crops in different VIF systems are reported on EUE_{total} for tomatoes (29.4-62.5 g_{FW} kWh^{-1}) (KOBAYASHI et al., 2022; ZEIDLER et al., 2017), potatoes (7.7-16.1 g_{FW} kWh^{-1} (KOBAYASHI et al., 2022) and wheat (1.1-2.3 g_{FW} kWh^{-1}) (ASSENG et al., 2020; KOBAYASHI et al., 2022). However, to optimize, gathering efficiency data for additional crops is crucial.

Strawberries are a high-value crop with increasing European consumption and cultivation trends (TOMMASO et al., 2021). However, their yield and quality are significantly influenced by cultivation conditions such as water availability, temperature fluctuations, pests, diseases, and post-harvest conditions (TOMMASO et al., 2021). These challenges and increasing consumer demand for strawberries outside the traditional season, including summer and winter, have led to an increase in closed production systems like polytunnels or glass greenhouses to improve yield and quality, reduce residues, and extend the harvesting period (SAMTANI et al., 2019; READ et al., 2021). Nevertheless, growing strawberries in greenhouses during summer and winter is challenging and demands substantial energy inputs. VIF offers a promising complement to existing systems, gaining interest because it enables year-round cultivation (GASTON et al., 2020; READ et al., 2021).

Moreover, VIF allows for targeted application of specific wavelengths, thus manipulating plant morphology and fruit quality like anthocyanins, which have anti-inflammatory effects and potentially further enhance the nutritional properties of strawberries. Flavonoids and anthocyanins protect the plant from UV and blue wavelengths (PANCHE et al., 2016; LANDI et al., 2021). Several studies indicate UV's positive effect on strawberries' anthocyanin content (WARNER et al., 2021). Nevertheless, there are still very few studies on the implementation of VIF for strawberry cultivation. Previous studies simulated VIF conditions in multilayer gatter systems in greenhouse conditions (HOFKENS et al., 2021; MADHAVI et al., 2023) or with artificial light as single layer Nutrient-Film-Technique (NFT) system (MAEDA and ITO, 2020). Recent studies in controlled VIF conditions showed the benefit of an added green or far-red LED light to the spectrum and increased light intensities on strawberry yields (ALVARADO-CAMARILLO et al., 2024; AVENDAÑO-ABARCA et al., 2023; RIES and PARK, 2024) or present solutions for automatic

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sensing and harvesting of strawberry fruits in VIF (Ren et al., 2024). The effect of additional UV$_A$ radiation on secondary metabolites of strawberry fruits in VIF are however not known. Furthermore data on the resource consumption of surface, water or energy and calculations of the efficiency in VIF are also missing.

In this study, we aimed to evaluate the efficiency parameters related to surface, water, and energy use efficiency across three strawberry cultivars with differing fruiting behavior: 'Mara de Bois' as Ever-bearing cultivar for its prolonged harvest season, 'Elsanta' as June-bearing (Read et al., 2021) cultivar for its high yield and market relevance (HY) and 'Mieze Schindler', a traditional, old June-bearing cultivar, with unique flavor but short post harvest (T). Additionally, we investigated the impact of two lighting strategies, white LEDs (full spectrum) and white LEDs supplemented with UV$_A$, on these parameters. Our objectives were to assess how cultivar and lighting strategy influence efficiencies and to evaluate the suitability of these cultivars with specific fruiting behaviors for VIF based on their morphological traits, fruit quality, and yield.

Material and methods

The container VIF used in this study is divided by a centrally placed entrance area in two identical growth units. One of the two growth units, equipped with six multilayer shelving racks, was used for the experimental setup. The total floor and growth area of the VIF unit were 14.2 m^2 and 20.2 m^2. Six racks with 4-5 layers (one layer offers a cultivation area of 0.84 m^2 with a distance of 42 cm from the layer above) were used.

Plant material

Strawberry plants (*Fragaria* × *ananassa*) were selected as a representative fruiting crop due to their high value and high market share, which makes them attractive for VIF. Three cultivars with different fruiting characteristics were chosen (Tab. 1). Two June-bearing (HY) strawberry cultivars, 'Mieze Schindler' and 'Elsanta', and one Ever-bearing strawberry cultivar, 'Mara de Bois'. According to German cultivar trials, 'Elsanta' and 'Mara de Bois' are well-known as high-yielding (Lafer, 2016; Stadler, 2016). 'Elsanta', a predominant strawberry cultivar in Germany, meets various production and market demands while offering moderate flavor. 'Mara de Bois' continues to flower as an Ever-bearing cultivar, ensuring a prolonged harvest season, whereas 'Elsanta', a June-bearing (HY) cultivar, flowers only once. 'Mieze Schindler', a traditional, old June-bearing (T) cultivar, also bears fruit in June but requires cross-pollination for fruit production. Despite its excellent taste, 'Mieze Schindler' has a short shelf life and lower yields.

Tab. 1: Characteristics of strawberry cultivars used in this study.

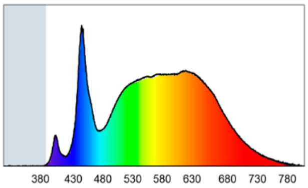
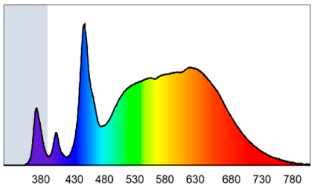
characteristic	cultivar A	cultivar B	cultivar C
designation	"June-bearing (HY)"	"Ever-bearing"	"June-bearing (T)"
cultivar	`Elsanta´	`Mara de Bois´	`Mieze Schindler´
flowering	june-bearing	ever-bearing	june-bearing
pollination	self-pollination	self-pollination	cross-pollination
shelf life *	long	short	short
taste *	moderate	excellent	excellent
marketable yield (kg m^{-2} a^{-1}) *	1.4-2.6	1.8-5.4	n.A.
marketable share (%) *	76-86	78	n.A.

* according to cultivar trials (Lafer, 2016; Stadler, 2016)
HY = High Yielding, T = Traditional

Light treatment: use of additional UV$_A$

As a basic light treatment, a white LED spectrum (L series NS12, Valoya, Sweden) was selected (treatment: white) (Tab. 2). Additional UV$_A$-LED-strips with a peak wavelength of 365 nm (Luxalight long Live, Luxalight, NLD) were added as a second light treatment (treatment: white+UV). The additional UV$_A$ at 365 nm accounted for 2.19 % of the PAR spectra, increasing overall PFD in the light treatment white+UV. The spectrum and irradiance were measured once for both treatments using a spectrometer with a wavelength range of 200-1100 nm at the cultivation level (Jaz, Ocean Optics Inc., USA). For both light treatments, an identical target light intensity of 320 ± 50 µmol m^{-2} s^{-1} at a measuring distance of 30 cm (LED to cultivation area) was set. PPFD was measured once for both

Tab. 2: Light treatments (white and white+UV) of the experiment.

Spectra		
Light treatment designation	white	white+UV
LED module	L-series, NS12 (Valoya, Sweden)	L-series, NS12 (Valoya, Sweden) Luxalight Long Live (Luxalight, NLD)
LED connecting power (W I W m^{-2})	28 I 167	64 I 252
Light output (μmol J^{-1})	11.4	5 (both LED models included)
PPFD I PFD (μmol m^{-2} s^{-1})	320 ± 50 I 341 ± 50	320 ± 50 I 349 ± 50
Photoperiod (h) (hh: mm – hh: mm)	18 h (09:00–03:00)	18 h (09:00–03:00)
DLI (mol m^{-2} d^{-1})	20.7 ± 3.2	20.7 ± 3.2
UV* I B* I G* I R* I FR* (%**)	0 I 18 I 38 I 39 I 6	2 I 17 I 37 I 38 I 6

* UV (300-400 nm) I Blue (401–500 nm) I Green „G" (501–600 nm) I Red „R" (601–700 nm) I far Red „FR" (701–800 nm)
** Share in percent regarding PFD
PPFD ranging from 400-700 nm; PFD ranging from 300-800 nm

light treatments at the cultivation level in a grid of 10 cm^2 using a photometer (LI-190R, LI-COR Inc., USA). With an 18 h photoperiod, a daily light integral (DLI) of 20.7 ± 3.2 mol m^{-2} s^{-1} was reached.

Experimental setup and cultivation

Strawberry plants (A++ grade, Frigo plants, KRAEGE Beerenpflanzen, Germany) of all three cultivars were prepared by removing soil and necrotic tissue, trimming roots, and placing them in net pots (Schlitztöpfe S, Pöppelmann, Germany). The plants were cultivated in deep-water, using euro-stacking boxes (0.4×0.3×0.12 m, AUER GmbH, Germany). Each box contained six plants in individual net pots of the same cultivar (plant density of 25 plants per meter square). For the first two weeks, desalinated external water was used. Subsequently, a nutrient solution was applied, consisting of major nutrients (in mM): 10.0 NO$_3$-N, 1.2 P, 3.0 Ca, 3.0 K, 2.0 Mg and micronutrients (in µM): 8.0 Mn, 0.5 Zn, 25.0 B, 0.5 Mo, 0.5 Cu, and 25.0 Fe mixed with internal water recovered from condensation. The nutrient solution was adjusted manually 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 solution level inside the box of 6 ± 2 cm. Six boxes per cultivar were randomized in one light treatment, respectively (Fig. 1).

A central black curtain prevented light contamination. The remaining cultivation area was filled with strawberry plants to ensure uniform growing conditions and representative calculations. Bumblebee hives (*Bombus terrestris*, Natupol Seeds, Koppert, Germany) were introduced for pollination. Air temperature was maintained at 20 °C during the day and 18 °C at night, with 60 % relative humidity. CO$_2$ concentration was kept at 1000 ppm using additional fumigation.

Resource efficiency calculations

The VIF operated entirely on electrical energy. Energy consumption for lighting, climate control, dehumidification, ventilation, and total energy use was continuously monitored using an energy data logger (Saia-Burgess Controls, Switzerland). EUE$_{light}$ for both light treatments was calculated as the ratio of produced fresh marketable biomass to cumulative electricity consumption for LED lighting (g$_{FW}$ kWh^{-1}) (Fig. 2).

To calculate the overall energy consumption of the container Vertical Indoor Farm (EUE$_{total}$) for both light treatments, energy consumption was modeled according to Wittmann et al., 2022. WUE represented the ratio of final marketable biomass to total water consumed (g$_{FW}$ l^{-1}). The container farm utilized condensers to recover water from evapotranspiration, ensuring a nearly closed hydroponic

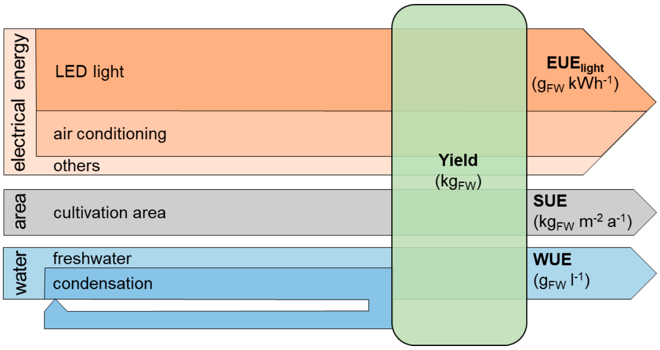


Fig. 2: Resources and calculated efficiencies

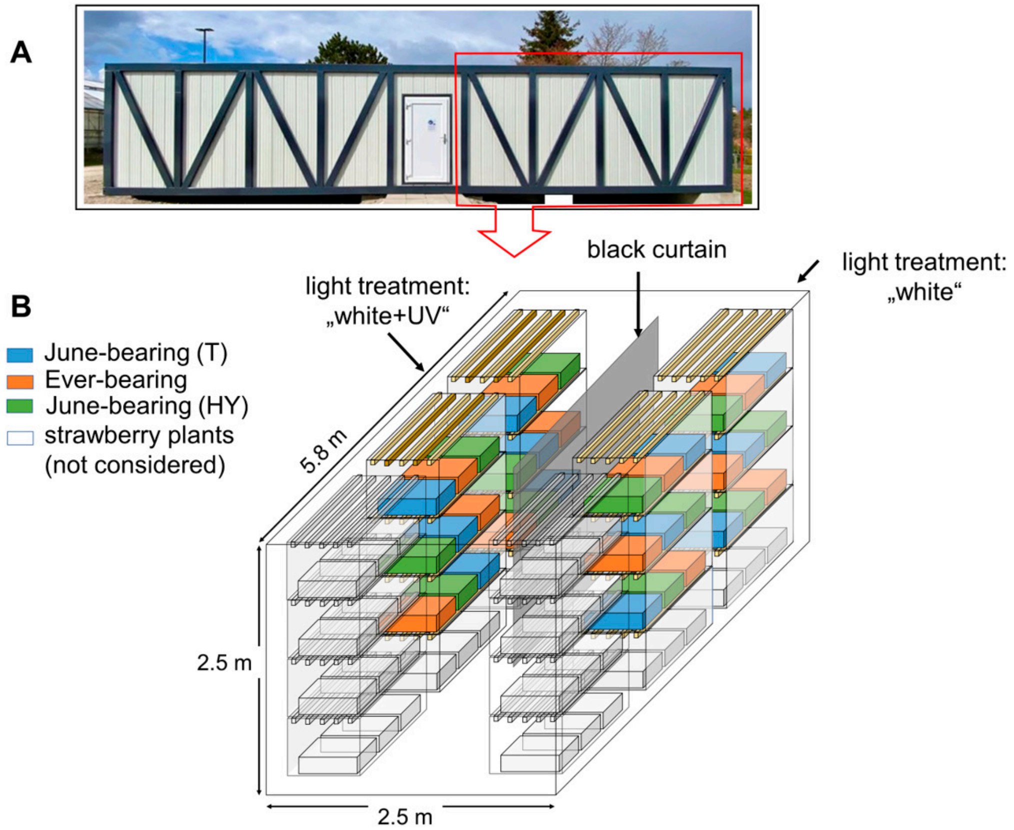


Fig. 1: (A) Container Vertical Indoor Farm, (B) experimental setup and positioning of treatments and multilayer racks. The color code of each box represents one replicate with six plants. A black curtain separated the light treatments “white” and “white+UV” to prevent light pollution by the additional UVA (365 nm) LED.

system with minimal water loss. Cumulative condensation from the cultivation unit was collected daily and proportionally allocated to each cultivation area. Water was supplied to each replicate box over the cultivation period, and the remaining water at the experiment's end was precisely quantified. Thus, the actual water consumed was calculated by subtracting the condensation and the remaining water from the total water supplied to each replicate box. SUE, representing the annual production of marketable biomass per unit area (kg_{FW} m^{-2} a^{-1}), was determined by multiplying the experimental yield of each treatment by the area of the cultivation box and subsequently scaling it to per meter square. The resultant value was further multiplied by the number of potential harvests per year to calculate the annual yield, contingent upon the duration of cultivation.

Fruit harvest and quality traits

Fully mature-looking fruits were harvested three times per week. Each harvested fruit was measured for fresh mass and fruit width. Additionally, fruit marketability was assessed according to the European marketing standard EU 543/2011 (European Commission, 2011), considering fruit health, diameter, and defects such as coloration, shape defects, or bruises. Fruits meeting the criteria for class extra were defect-free and reached a diameter of at least 25 mm. The class I included fruits with minor defects (covering less than 10 % of the fruit area) and a diameter of at least 18 mm. Given the high-quality expectations in VIF, only fruits classified as extra or class I were considered in the results. Fruits labeled class II, typically marketable, were marked as non-marketable and excluded from yield calculations.

Organoleptic quality parameters

For analysis, once per week, a random sample of 10 defect-free fruits per treatment and cultivar were selected, totaling 30 fruits. Firmness was measured using a penetrometer (3.5 mm FirmTech FT7, UP, Germany), with results reported in g mm^{-1}. The sample was further divided into a subsample of 21 fruits for acidity and sugar content determination and 9 for anthocyanin and vitamin C analysis. The 21 fruits were homogenized at 24,000 rpm using an ultra-turrax (IKA Ultra-Turrax T25, Janke & Kunkel), followed by centrifugation (10,000 rpm, 5 min, 4 °C, Heraeus Megafuge X1R Centrifuge, Thermo Scientific). The resulting supernatant was used to determine sugar concentration (°Brix) via a handheld refractometer (Hi 96822, Hanna Instruments, Germany).

Analysis of anthocyanins and ascorbic acid

The subsample of 9 fruits per treatment was immediately treated in liquid nitrogen, frozen at -80 °C, and further freeze-dried and pulverized. Anthocyanins were extracted and quantified according to the method described by Mewis et al., 2011. The Anthocyanates were quantified against the external standard cyanidin chloride (PhytoPlan). Single anthocyanins were identified on a Thermo Scientific LXQ ESI-Ion Trap mass spectrometer to identify the single peaks (positive ion mode). For instrument control and data processing, the software Thermo Xcalibur Version 2.2 SP1.48 was used. For the quantification of ascorbic acid (also known as vitamin C), a modified method described by Gu et al., 2018 and Tiwari et al., 2009 was used. A volume of 10 µl extract was injected and separated using an AcclaimTM RP18 column (3 µm, 120 Å, 2.1×250 mm, Thermo Scientific). Isocratic separation was performed at a 0.6 ml/min flow rate using the following eluent: 25 mmol KH2PO4: acetonitrile, 95:5 (v/v). The oven temperature was 30 °C. Detection was carried out at 254 nm on a photodiode array detector. Ascorbic acid was quantified using a calibration curve from a chemical reference (Fluka). For both methods, extracts were quantified by HPLC (Ultimate 3000, Thermo Scientific). For peak evaluation, the Chromeleon version 7.2 software was used.

Growth analysis

Each plant's height, diameter, and number of leaves were individually recorded after cultivation. Leaf and root fresh biomass were quantified, followed by the determination of dry biomass after drying at 60 °C for 72 h. Plant leaf area was measured before drying using a leaf area meter (LI-3100C Area Meter, LI-COR Inc., USA), and specific leaf area (SLA) was calculated as the ratio of leaf area to dry mass (cm^2 g^{-1}). The leaf area index (LAI) was calculated by dividing the plant leaf area by the occupied cultivation area (number of plants per box). The Harvest Index was also determined as the proportion of marketable fresh fruit relative to the total produced plant biomass (leaves, roots, runners).

Statistics

The experimental design followed a randomized block design with six experimental units per light treatment. Each replication consisted of a box containing six strawberry plants, three designated edge plants, and three used for data analysis, all randomly arranged within the box. Randomization of plants within each box and boxes within each tier minimized placement effects. After completion, the data from individual plants within each box were averaged to obtain a mean value per replication for statistical analysis. Organoleptic quality parameters were gathered for every single fruit and averaged per plant. Statistics on anthocyanins and ascorbic acid were done on single fruits. Effects of light treatment with UV_A and strawberry cultivars on efficiencies, fruit quality, and plant growth were analyzed via two-way ANOVA (ANOVA, Minitab 21st edition, Minitab GmbH, Germany). A significance level of $p \leq 0.05$ was applied, with normality assessed using Kolmogorov-Smirnov tests and data transformed as necessary to meet normal distribution assumptions.

Results

Growing parameter and yield

In total, 5,300 fresh strawberry fruits (26.5 kg_{FW}) with full maturity were harvested and classified according to fruit width and defects. The Ever-bearing variety produced significantly more fruit, with yields of 697.6 ± 72.2 g (white) and 611.9 ± 71.5 g (white+UV), compared to the June-bearing (HY) variety (530.2 ± 107.4 g and 476.3 ± 22.7 g) and the June-bearing (T) cultivar (160.3 ± 33.3 g and 139 ± 43.1 g) (Fig. 3).

Additionally, the proportion of extra and class I fruits in the Ever-bearing variety was significantly higher than in class II and not marketable categories. In the June-bearing (HY) cultivar, the proportion of not marketable fruit was comparable to extra and class I but significantly lower in class II. The June-bearing (T) cultivar had the highest proportion of fruit in class I, with other categories being comparable.

The Ever-bearing strawberry cultivar had a nine-week harvest phase, compared to seven weeks for the June-bearing (HY) and five weeks for the June-bearing (T) cultivar (Fig. 4).

Cultivation times until harvest were six weeks for both the Ever-bearing and June-bearing (HY) cultivars and eight weeks for the June-bearing (T) cultivar. Three potential harvests per year are feasible for the Ever-bearing, 3.8 for the June-bearing (HY), and 3.2 for the June-bearing (T) cultivar. The Ever-bearing cultivar yielded 4.4 ± 0.5 kg m^{-2} (white) and 4.2 ± 0.7 kg m^{-2} (white+UV), significantly higher than the June-bearing (HY) (2.3 ± 0.1 kg m^{-2} and 2.6 ± 0.5 kg m^{-2}) and June-bearing (T) cultivars (0.6 ± 0.2 kg m^{-2} and 0.8 ± 0.2 kg m^{-2}). No significant differences were found between light strategies.

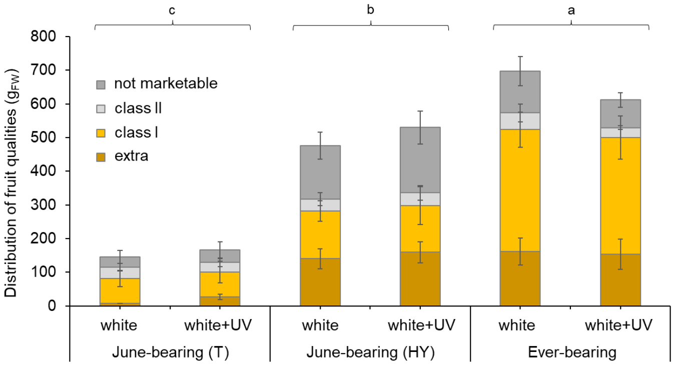


Fig. 3: Distribution of fruit qualities of strawberry fruits grown in a Vertical Indoor Farm and classified according to marketing standards and per treatment. Treatments included three different strawberry cultivars with different fruiting characteristics (Ever-bearing and high-yielding, June-bearing (HY = high-yielding), June-bearing (T = traditional/old) cultivar) and two artificial light strategies (LED); white light and white light with additional UV_A. Results of an ANOVA on the sum of fruits per treatment were added and indicated as different letters (n = 6, Tukey, $p < 0.05$). Error bars represent the standard deviation.

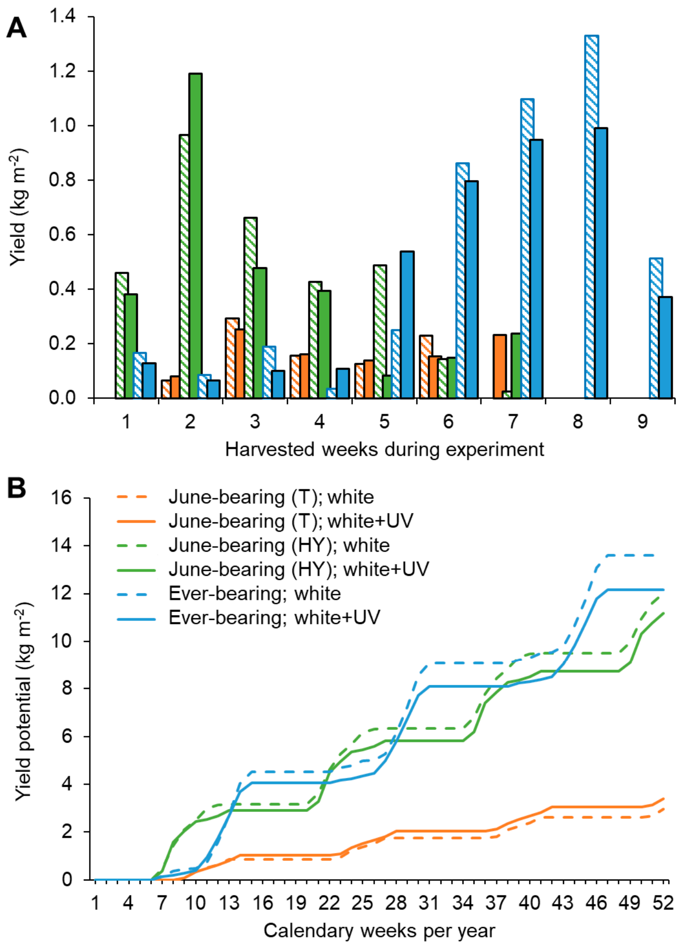


Fig. 4: The yield (A) per week during harvest and (B) the potential cumulative yield per square meter of fresh strawberries is shown for three strawberry cultivars with different fruiting characteristics (Ever-bearing and high-yielding, June-bearing (HY = high-yielding), June-bearing (T = traditional/old) cultivar) and two artificial light strategies; white light (dashed bar or line) and white light with additional UV_A (filled bar or line) LED light.

Based on our analysis, the Harvest Indices for Ever-bearing were 0.81 ± 0.04 (white) and 0.79 ± 0.05 (white+UV). These values were significantly higher than those for the June-bearing (HY) cultivar (0.59 ± 0.00 and 0.66 ± 0.03), as well as for June-bearing (T) cultivar, which had values of 0.28 ± 0.06 and 0.31 ± 0.07 (Fig. 5).

The Ever-bearing cultivar also had significantly more fruits per plant (30.3 ± 4.0 and 26.8 ± 2.5 fruits), followed by June-bearing (HY) (11.1 ± 1.7 and 12.1 ± 2.8 fruits) and June-bearing (T) (4.0 ± 2.7 and 3.8 ± 2.0 fruits). The significantly highest fruit yield per plant was seen in the Ever-bearing cultivar (178.2 ± 15.2 g and 153.3 ± 18.5 g). The June-bearing (HY) had significantly the heaviest fruits (8.8 ± 1.2 g and 8.1 ± 0.7 g). Non-marketable biomass, including stems, leaves, and roots, was lowest in the Ever-bearing cultivar (123.3 ± 5.7 g and 131.6 ± 20.4 g), while June-bearing (HY) and June-bearing (T) showed no significant differences. UV_A treatment had no significant effect on any of these parameters. The plants reached comparable heights ranging from 15-23 cm and a Leaf Area Index (LAI) of 9.7-14.4 cm^2 cm^{-2}) (Tab. 3). Although there was a trend towards higher LAI values with additional UV_A, this was not statistically significant. The Ever-bearing cultivar had the significant highest Specific Leaf Area (SLA) at 116.9 ± 3.0 cm g^{-1} (white) and 149.0 ± 28.5 cm g^{-1} (white+UV). Additional UV_A had no significant effect on SLA.

Fruit quality

Fruit firmness did not differ significantly between the cultivars, although the June-bearing (T) cultivar had, on average, lower firmness than the ever- and June-bearing (HY) cultivars. The Brix level was significantly higher in the June-bearing (T) cultivar (12.5 ± 0.2 °brix and 11.9 ± 1.3 °brix for white and white+UV), but showed no significant effect from additional UV_A.

When examining total anthocyanins and ascorbic acid (vitamin C), we found that additional UV_A treatment did not influence their levels significantly (Fig. 6). However, the ascorbic acid content was significantly highest in the Ever-bearing cultivar with 37.39 ± 2.2 mg $100g_{FW}^{-1}$ (white) and 35.7 9 ± 3.9 mg $100g_{FW}^{-1}$ (white+UV). The anthocyanin content was in the Ever-bearing cultivar (59.79 ± 10.5 mg $100g_{FW}^{-1}$ and 56.59 ± 13.2 mg $100g_{FW}^{-1}$ for white and white+UV) but also in the June-bearing (T) cultivar significantly higher compared to the June-bearing (HY) cultivar. The Ever-bearing cultivar demonstrated significantly higher potential annual yields of ascorbic acid and anthocyanin content than the other treatments.

Efficiency parameters

SUE varied significantly across cultivars (Fig. 7). The Ever-bearing cultivar showed the significant highest SUE values: 15.2 ± 1.6 kg_{FW} m^{-2} a^{-1} under white light and 14.5 ± 2.4 kg_{FW} m^{-2} a^{-1} with additional UV_A , compared to the June-bearing (HY) cultivar, which achieved 9.4 ± 0.6 kg_{FW} m^{-2} a^{-1} and 10.9 ± 2.0 kg_{FW} m^{-2} a^{-1}, respectively, and the June-bearing (T) cultivar (2.3 ± 0.8 kg_{FW} m^{-2} a^{-1} and 2.9 ± 0.9 kg_{FW} m^{-2} a^{-1}) respectively. WUE varied significantly among cultivars. The Ever-bearing cultivar demonstrated the highest WUE values. Under with light, values of 291.7 ± 33.7 g_{FW} l^{-1} were reached. With additional UV_A, values of 267.6 ± 33.7 g_{FW} l^{-1} were documented. The June-bearing (HY) cultivar showed lower WUE values. Under white light, an efficiency of 114.6 ± 22.0 g_{FW} l^{-1} was reached. With additional UV_A a WUE of 173.5 ± 40.5 g_{FW} l^{-1} was documented. The June-bearing (T) cultivar demonstrated the lowest WUE values. Under white light, it achieved 72.0 ± 29.4 g_{FW} l^{-1}. With additional UV_A it reached 83.6 ± 29.7 g_{FW} l^{-1}. Importantly, UV_A treatment did not significantly affect these efficiency parameters across all cultivars.

The Ever-bearing cultivar achieved higher EUE values under white light (10.6 ± 1.1 g_{FW} kWh^{-1}) compared to with additional UV_A

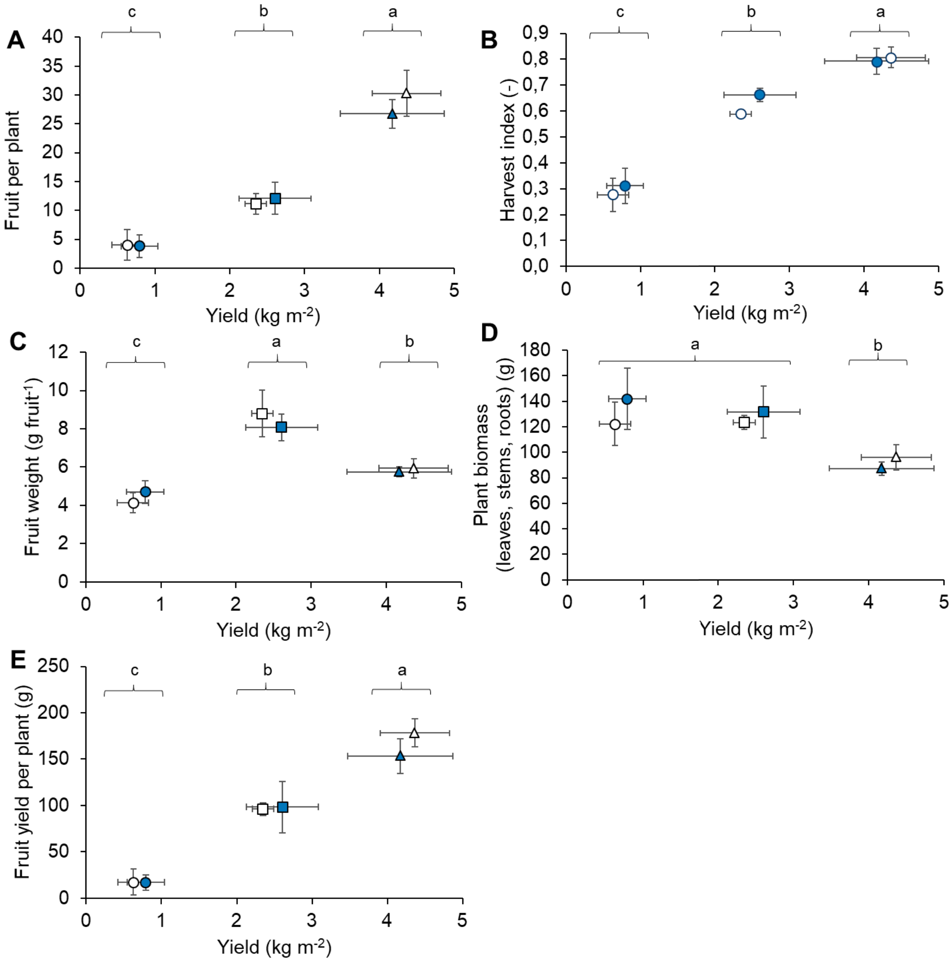


Fig. 5: Results on class extra and class I strawberry fruits cultivated in Vertical Indoor Farm. Results are given in comparison to the strawberry yield for three cultivars with different fruiting characteristics (Ever-bearing and high-yielding, June-bearing (HY = high-yielding), June-bearing (T = traditional/old) cultivar) and two artificial light strategies (LED); white light (open symbol) and white light with additional UV_A (blue symbol) LED light. (A) Number of fruits per plant, (B) Harvest Index (ratio between marketable yields to overall biomass), (C) individual fruit weight, (D) not-marketable biomass, (E) yield of strawberry fruit per plant. Error bars show the standard deviation of the mean. Results of an ANOVA (light treatment and cultivar) on the shown parameters are added and indicated as different letters (n=6, Tukey, $p < 0.05$). Error bars represent the standard deviation.

Tab. 3: Results are given in comparison to the strawberry yield for three cultivars with different fruiting characteristics (Ever-bearing and high-yielding, June-bearing (HY = high-yielding), June-bearing (T = traditional/old) cultivar) and two artificial light strategies (LED); white light and white light with additional UV_A. LAI = leaf area index, SLA = specific leaf area, TSS = total soluble solids. Results on a two-way ANOVA (light treatment and cultivar) on the shown parameters are added and indicated as different letters (n=6, Tukey, $p < 0.05$). Error bars represent the standard deviation.

cultivar	**light strategy**	**plant height (cm)**	**LAI (cm^2 cm^{-2})**	**SLA (cm^2 g^{-1})**	**firmness (kg cm^{-2})**	**TSS (°brix)**
June-bearing (T)	white	15.0 ± 2.2 a	10.0 ± 1.8 a	73.4 ± 5.9 b	100.7 ± 10.3 a	12.5 ± 0.2 a
	white+UV	17.5 ± 3.4 a	14.1 ± 1.8 a	80.8 ± 7.1 b	113.4 ± 13.4 a	11.9 ± 1.3 a
June-bearing (HY)	white	21.0 ± 1.3 a	9.7 ± 2.1 a	72.5 ± 7.5 b	172.1 ± 9.8 a	7.9 ± 0.5 b
	white+UV	23.5 ± 2.4 a	11.2 ± 5.0 a	83.5 ± 6.3 b	173.5 ± 21.7 a	7.1 ± 0.4 b
Ever-bearing	white	18.6 ± 1.4 a	12.3 ± 2.0 a	116.9 ± 3.0 a	144.4 ± 19.6 a	7.7 ± 0.9 b
	white+UV	19.9 ± 3.1 a	14.4 ± 3.9 a	149.0 ± 28.5 a	159.2 ± 4.0 a	7.4 ± 0.7 b

(6.8 ± 1.1 g_{FW} kWh^{-1}) (Fig. 7). Similarly, for EUE_{light}, the Ever-bearing cultivar showed higher efficiencies under white light (15.2 ± 1.6 g_{FW} kWh^{-1}) compared to additional UV_A (9.6 ± 1.6 g_{FW} kWh^{-1}). The June-bearing (HY) cultivar achieved lower efficiencies under both white light (6.5 ± 0.4 g_{FW} kWh^{-1}) and additional UV_A (5.2 ± 0.9 g_{FW} kWh^{-1}), while the June-bearing (T) cultivar consistently exhibited the lowest efficiencies (1.7 ± 0.6 g_{FW} kWh^{-1} under white light and 1.4 ± 0.4 g_{FW} kWh^{-1} with additional UV_A).

The additional UV_A LEDs did indicate a significant increase in the consumed electricity of 3.1-4.7 kWh m^{-2} d^{-1} regarding the lighting system (LEDs) and an increase of 1.0-1.5 kWh m^{-2} d^{-1} for the climatization (Fig. 8). In total, the electricity consumption increased

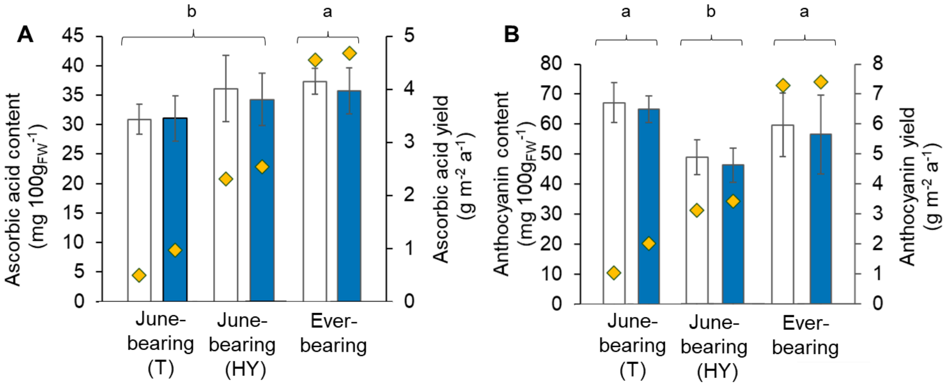


Fig. 6: Fruit quality parameters of strawberries grown in a Vertical Indoor Farm for three cultivars with different fruiting characteristics (Ever-bearing and high-yielding, June-bearing (HY = high-yielding), June-bearing (T = traditional/old) cultivar) and two artificial light strategies (LED); white light (open bar) and white light with additional UV$_A$ light (blue bar). (A) Ascorbic acid (Vitamin C) and (B) anthocyanins content per 100 g fresh weight is shown on the left axis, and the annual yields in g per square meter (yellow diamond) on the right axis. Error bars show the standard deviation. Results of an ANOVA on the shown parameters are added and indicated as different letters (n=6, Tukey, $p < 0.05$). Error bars represent the standard deviation.

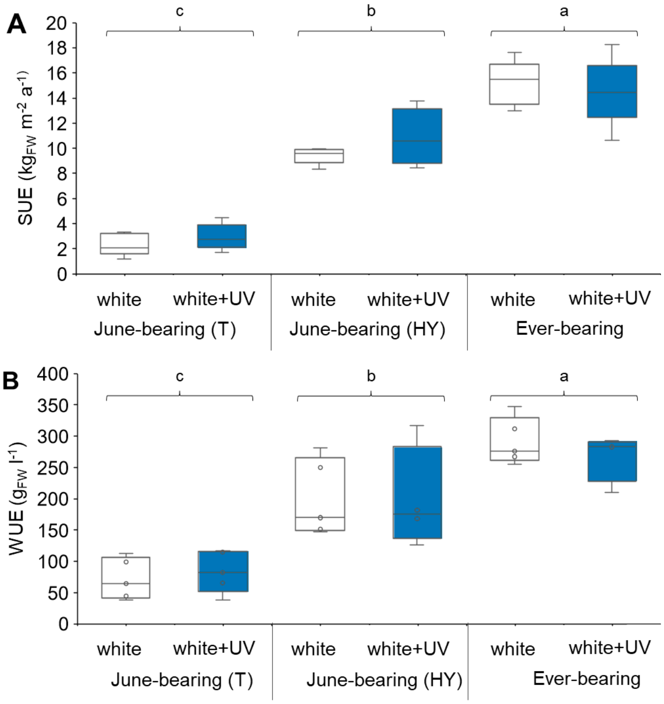


Fig. 7: Results on resource efficiency for class extra and class I strawberry fruits cultivated in a Vertical Indoor Farm for three cultivars with different fruiting characteristics (Ever-bearing and high-yielding, June-bearing (HY = high-yielding), June-bearing (T = traditional/old) cultivar) and two artificial light strategies (LED); white light (open bar) and white light with additional UV$_A$ LED (blue bar) light. (A) Surface use efficiency (SUE) and (B) water use efficiency (WUE). Results of an ANOVA on the shown parameters are added and indicated as different letters (n=6, Tukey, $p < 0.05$). The horizontal line in the box is the median, the x is the average, the upper and lower edges of the box are the 25 and 75 percentiles, and the error bars indicate the minimum and maximum number in the data set. Circles mark the data points.

by using UV$_A$ LEDs from 4.5-6.6 kWh m^{-2} d^{-1}. There was no effect on dehumidification and ventilation. The energy consumption of the VIF containers remained constant throughout the cultivation period and, according to the model, also throughout the year, fluctuating only between 4.1 and 4.4 kWh m^{-2} d^{-1} (data not provided).

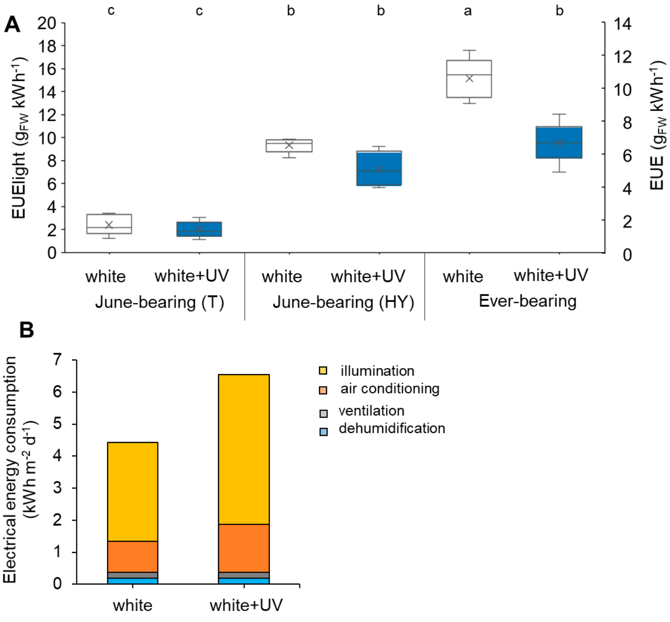


Fig. 8: Results on (A) the total energy use efficiency and the light energy use efficiency (EUE$_{total}$ and EUE$_{light}$) as well as (B) the energy consumption for class extra and class I strawberry fruits cultivated in a Vertical Indoor Farm. Results are shown for (A) regarding three cultivars with different fruiting characteristics (Ever-bearing and high-yielding, June-bearing (HY = high-yielding), June-bearing (T = traditional/old) cultivar) and two artificial light strategies (LED); white light and white light with additional UV$_A$. In (B), both light treatments are compared in terms of total energy consumption. Results of an ANOVA on efficiency parameters are added and indicated as different letters (n=6, Tukey, $p < 0.05$). The horizontal line in the box is the median, the x is the average, the upper and lower edges of the box are the 25 and 75 percentiles, and the error bars indicate the minimum and maximum number in the data set. Circles mark the data points.

Discussion

Enhancing energy efficiency is essential for the future viability of VIF, alongside crop quality, market competitiveness, and localized production. Strawberries were selected as a model crop due to their high value and short shelf life, meeting increasing off-season demand in Europe.

Yield and surface use efficiency (SUE)

The SUE varied significantly (2.3-15.2 kg_{FW} m^{-2} a^{-1}) and was influenced by the fruiting characteristics of the chosen cultivars. The Ever-bearing cultivar's higher SUE can be explained due to an extended 96-day harvest period compared to 81-86 days for June-bearing (HY) cultivars, a significantly increased fruit production per plant, lower proportions of non-marketable fruits, and a higher harvest index. Although the June-bearing (HY) cultivar had significantly larger individual fruit weights, fewer fruits per plant resulted in a lower yield per plant (96.2 ± 6.8 g_{FW} $plant^{-1}$) than the Ever-bearing cultivar (178.2 ± 15.2 g_{FW} $plant^{-1}$). Literature indicates yields up to 349 g_{FW} $plant^{-1}$ under comparable light intensity and white LED. In open fields or greenhouses, yields range from 120-340 g_{FW} $plant^{-1}$ (Elsanta) to 164-900 g_{FW} $plant^{-1}$ (Mara de Bois). Even though class II fruits were excluded from our study, further yield increases in VIF can be expected. The high harvest index in the Ever-bearing (0.81) and June-bearing (HY) (0.66) cultivars contrasts with the documented index of 0.31-0.34 for the open fields (FERNANDEZ et al., 2001). VIF conditions likely allocated more resources to fruit production than non-marketable biomass, evident from the low plant height (15-23 cm) and non-marketable plant biomass in the Ever-bearing cultivar (123.3-131.6 g $plant^{-1}$). Furthermore, the significantly higher SLA of the Ever-bearing cultivar (116.9-149.0 cm^2 g^{-1}) exceeded the typical SLA for strawberries (77-116.8 cm^2 g^{-1}) (FERNANDEZ et al., 2001). An increased SLA suggests optimal adaptation to conditions by developing thinner, light-absorbing leaves, which could have potentially increased photosynthesis and ultimately enhanced efficiency and yield. The comparable SUE to greenhouse production (9-14 kg_{FW} m^{-2} a^{-1}) and higher SUE than the open field (3.1-8.6 kg_{FW} m^{-2} a^{-1}) were presumably achieved by higher planting densities and multiple yearly cultivation periods. Typical lower planting densities for strawberries in greenhouses (6-10 plants per m^2) and open fields (3-8 plants per m^2) were reported (PARANJPE et al., 2008). Higher plant densities, ranging from 11-25 plants per m^2, have been shown to increase strawberry yields (DE CAMACARO et al., 2004). Therefore, our trial with 25 plants per m^2 shows promising results for significantly higher SUE in Ever-bearing cultivars with further cultivation optimization.

Fruit quality

The fruit quality of fresh strawberries is critical to meet market demands. The three cultivars used in this study generally met market quality requirements. However, despite the homogeneous conditions in VIF, there was a proportion of non-marketable fruits ranging from 18-25% (including class II as non-marketable) and 13-18% (exclusively non-marketable fruits), comparable to typical rates of 14-22% of non-marketable fruits. The June-bearing (HY) cultivar even showed higher proportions, up to 40%, highlighting the need to further optimize crop management to increase the proportion of class extra and class I fruits in VIF. The application of UV_A showed an average reduction in non-marketable fruits, although this reduction was not statistically significant. Similar observations have been mentioned in studies suggesting a positive effect of UV on crop yield due to reduced pathogens in strawberries (ONOFRE et al., 2022, 2021). As expected, the June-bearing (T) cultivar, known for its sweet taste and soft fruit skin, exhibited the lowest fruit firmness but the highest content of total soluble solids (TSS) compared to the June-bearing (HY) and Ever-bearing cultivars (12 °Brix compared to 8 °Brix). These results are consistent with literature values for TSS (5.6-14.5 °Brix) in strawberries (CERVANTES et al., 2020; HASING et al., 2013; MENZEL, 2023). VIF is intended to enhance the production of high-quality crops with increased secondary metabolites and minerals, such as vitamin C (ascorbic acid) and anthocyanins (GIAMPIERI et al., 2012), with UV wavelengths known to promote anthocyanin biosynthesis (LOCONSOLE and SANTAMARIA, 2021). Several studies have reported values between 13.4-60.0 mg 100 g_{FM}^{-1} for anthocyanins and 28.0-85.3 mg 100 g_{FM}^{-1} for vitamin C in fresh strawberries (GIAMPIERI et al., 2012; HAZARIKA et al., 2019; MOOR et al., 2005). Strawberry fruits in our experiment showed comparable anthocyanins (48-67 mg 100 g_{FM}^{-1}) and vitamin C contents (30-37 mg 100 g_{FM}^{-1}). However the Ever-bearing cultivar exhibited significantly higher levels of vitamin C and anthocyanins than the June-bearing (HY) cultivar, potentially yielding significantly higher amounts of both compounds annually in VIF due to its high SUE. According to the literature next to pre-harvest factors light intensity and temperatures are influencing the final vitamin C contents of horticultural crops. The additional UV_A exposure had no significant effect on vitamin C contents or on anthocyanin levels. Literature report mixed findings, with some studies indicating that combined UV-LED irradiation at 254, 306, and 352 nm increases anthocyanin content in strawberries (KIM et al., 2011), while others show no effect (KUMAR, 2021). However, it can be assumed that the higher Leaf Area Index (LAI) of 12-14 cm^2 cm^{-2} compared to a greenhouse or open field production of 3.3-4.3 cm^2 cm^{-2} (SIM et al., 2020) could have reduced fruit exposure to the UV_A LEDs.

Water- and Energy Use Efficiency (WUE and EUE)

One known advantage of VIF is its high WUE, which is significantly influenced by the yield potential of the cultivars used. Our experiment documented a WUE of up to 291 g_{FW} l^{-1} in the Ever-bearing cultivar. The June-bearing (T) cultivar showed significantly lower WUE values of 72–83 g_{FW} l^{-1}. Compared to these, reported values of WUE's on strawberries in tunnel cultivation with drip irrigation are lower (15-24 g_{FW} l^{-1}) (ARIZA et al., 2021). They also exceed the WUE values reported for basil and lettuce in VIF studies, which range from 38-60 g_{FW} l^{-1} (KOBAYASHI et al., 2022; PENNISI et al., 2020). This difference may be due to the fully closed recirculating hydroponic system in the container VIF, where external water input was limited to the initial fresh water supply.

Similarly, EUE showed a wide range between 1.4-10.6 g_{FW} kWh^{-1} (EUE_{total}) and 2.0-15 g_{FW} kWh^{-1} (EUE_{light}). The Ever-bearing cultivar achieved the highest EUE_{total} and EUE_{light}, which are comparable to EUE_{total} values reported for potatoes (7.7-16.1 g_{FW} kWh^{-1}; (KOBAYASHI et al., 2022), higher compared to wheat (1.1-2.3 g_{FW} kWh^{-1}; (ASSENG et al., 2020; KOBAYASHI et al., 2022), but lower compared to 29.4-62.5 g_{FW} kWh^{-1} for tomatoes (KOBAYASHI et al., 2022; ZEIDLER et al., 2017). In our experimental setup, the used container VIF system required up to 4.4 kWh m^{-2} d^{-1}. With additional UV_A, total energy use increased significantly to 6.4 kWh m^{-2} d^{-1}, possibly due to the lower efficiency of UV-LEDs in converting electrical energy into light energy (JANSEN and ALBERT, 2018). High-tech greenhouses in the Netherlands report annual total energy supplies of 1.4-3.0 kWh m^{-2} d^{-1} (0.7-0.8 kWh m^{-2} d^{-1} for heating and 0.7-1.2 kWh m^{-2} d^{-1} for artificial light) (KATZIN et al., 2021), which is less than half. However, direct comparisons between greenhouse and VIF production are challenging due to differences in energy usage. Greenhouses need thermal energy for heating and electricity for cooling and lighting, while VIF relies solely on electricity for climate control and lighting. Further system efficiency improvements and maximizing the use of all plant parts, including by-products, can enhance VIF performance. Despite its high energy consumption, VIF's consistent and manageable energy use could benefit future smart grid applications.

Conclusions

Our study highlights the potential of Vertical Indoor Farming (VIF) for efficiently producing high-quality strawberries. The Ever-bearing cultivar demonstrated a high SUE with an extended harvest period and an increased fruit production per plant, resulting in higher WUE than other reports for VIF. This cultivar also showed the highest Harvest Index and Specific Leaf Area, indicating efficient use of resources for fruit production. Despite challenges with non-marketable fruits, the fruit quality, including vitamin C and anthocyanin content, met market standards. Notably, the Ever-bearing cultivar achieved significantly higher potential annual yields of ascorbic acid and anthocyanin content compared to other treatments. The container VIF system required initial external water input only and maintained cultivation for up to 110 days exclusively on internal water circulation. While additional UV_A treatment did not significantly affect most parameters, it did increase overall energy consumption, suggesting a need for further optimization of lighting strategies in VIF systems.

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Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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