agronomy

Article

Energy Efficient Lighting in Plant Factories: Addressing Utilance

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Abstract: Vertical farming is considered to play a crucial role in future food supply. Until today, the high amount of electrical energy required for artificial lighting has been problematic in this context. Various possibilities for increasing efficiency through adapted lighting conditions have been and are being investigated. However, comparably little attention is paid to increasing utilance, i.e., the amount of photons that can effectively be used by the plant. In this work, a novel targeted lighting strategy is therefore proposed that allows for a dynamic adaptation of the luminaires' light distribution to match the effective crop size at each stage of plant growth in a fully-automated manner. It is shown that the resulting utilance can significantly be increased compared to standard full-coverage lighting. Moreover, it is found that the proposed strategy is likely to consume less than half of the electrical energy usually required for the latter. An additional increase in system efficiency can be prognosticated and the potential energy savings are estimated based on assumptions of future LED generations derived from literature.

Keywords: horticultural lighting; dynamic light distribution; targeted lighting; utilance; LED lighting

Citation: Balasus, J.; Blank, J.; Babilon, S.; Hegemann, T.; Khanh, T.Q. Energy Efficient Lighting in Plant Factories: Addressing Utilance. *Agronomy* **2021**, *11*, 2570. https://doi.org/10.3390/agronomy11122570

Academic Editor: Byoung Ryong Jeong

Received: 31 October 2021
Accepted: 15 December 2021
Published: 17 December 2021

1. Introduction

Vertical indoor farming comes along with a lot of benefits ranging from a stable year-round production, high productivity, and crop quality to higher yields per land area and less impact on the environment due to the development of water-, fertilizer-, and pesticide-saving cultivation methods [1–5]. The cultivation of crops in such closed environments allows for the explicit and optimal control of environmental parameters affecting plant growth [6], but at the same time requires natural daylight to be replaced by artificial light sources to drive the process of photosynthesis [7–9], which considerably increases the demand for (electrical) energy. In the earlier days, fluorescent tubes were used for this purpose. However, starting from 2015, LED-based solutions have become the state-of-the-art technology in horticultural lighting [10].

Even though modern LED packages and chip-on-board (COB) modules with high efficiencies are used as light sources, the amount of electrical energy needed for production is often stated to be the limiting factor for a broad scale application of vertical and indoor farming technologies. The reported amounts of electrical energy typically needed for horticultural lighting in plant factories vary between studies and range from 52 % (calculated with data from [11]) up to 80 % [12] of the total energy required for an optimal plant growth. To produce a single head of lettuce, this translates to an electrical energy consumption of approximately 1.0–1.6 kW h that can be referred to lighting. Nonetheless, in terms of overall energy consumption per produced kilogram dry weight, vertical indoor farms have been shown to outperform even the most efficient greenhouses [13]. However, the general demand of such plant factories for purchased energy is much higher than in the latter case and reduces corresponding profit margins.

In recent years, though, developments in horticultural lighting have introduced new sustainability concepts intended to significantly reduce the electrical energy consumption of modern indoor farming. In this context, a distinction can be made between such concepts that aim at physiological aspects to improve plant growth and those that focus more on the technical parts of lighting. Regarding the former, various studies have shown that the growth of crops, plants, and specific plant parts can be optimized by adjusting the spectral composition [14–17], the intensity[18–20], and the timing [20–22] of light exposure, whereas most technical approaches aim at increasing the conversion rate from electrical energy to usable optical radiation by optimizing the lighting fixtures including their light output characteristics.

An important measure in this context is the so-called photosynthetic photon flux efficacy (PPFE), which is defined as the number of photons within the spectral region of photosynthetically active radiation (PAR) emitted by the luminaire divided by the electrical energy required for their creation and is expressed in $\mu mol\,J^{-1}$. The latest generation of horticultural luminaries with either a blue/red or white/red LED mixture typically yield conversion efficacies of $3.0\,\mu mol\,J^{-1}$ and $2.78\,\mu mol\,J^{-1}$, respectively. However, based on theoretical deliberations on physical limitations, Kusuma et al. [23] prognosticated efficacies of $4.1\,\mu mol\,J^{-1}$ for the blue/red and of $3.4\,\mu mol\,J^{-1}$ for the white/red solutions to be achievable with current LED technologies.

Besides increasing the PPFE of a luminaire, it is important to ensure that the emitted photons can efficiently be used by the plant. Ideally, each photon generated from electrical energy should reach its usable area, i.e., the plant leaves. Thus, the larger the ratio between the photon flux reaching the plant leaves and the total flux emitted by all relevant light sources, the higher the overall efficiency of the horticultural lighting system. In this context, Lee et al. [24] were able to show that the use of dedicated LED-lens combinations for targeted beam shaping may increase the lighting system's efficiency with regard to crop cultivation by almost a factor of four compared to using conventional fluorescent luminaires. System efficiency in horticultural lighting, however, does not only depend on the light sources' emission characteristics but also on the absolute distance between the luminaire and the plant leaves.

To obtain an estimate for the amount of usable photons, the canopy photon capture efficiency (CPCE) has been introduced as a reliable measure in horticultural lighting and is basically determined by the fraction of emitted photons reaching the plant leaves [25]. As plant growth, in general, is not linear, the resulting canopy density ($\widehat{=}$ leaf area index) is changing over time. Thus, in order to ensure a constantly high CPCE across all growth phases, the distance between the lighting fixtures and the growing plants must be adjusted continuously in case of a steady illumination [26]. This adjustment process, however, requires additional human interaction or at least the implementation of a dedicated (electro)mechanical system, both leading to increments in working hours and/or electrical power consumption.

Instead of using a steady illumination in combination with a continuous distance adjustment, a better and more sophisticated way of ensuring a constant CPCE is to adapt the lighting fixtures' spatial light distributions to comply with the changing canopy density. Even though such targeted lighting strategies have been shown to significantly increase the energy-biomass conversion efficiency [27,28], i.e., the produced biomass per unit of electrical energy, previous implementations and proof-of-concepts found in the literature still require manual adjustments over time for achieving optimal results. For this reason, the purpose of the current work is to present a novel, fully-automated lighting strategy that, by making use of a specifically designed luminaire, automatically adapts the light distribution to match the effective leaf surface area at each stage of plant growth in order to minimize the wasting of optical radiation.

2. Materials and Methods

2.1. Dynamic Utilance

According to CIE S 017/E:2020 [29], the quantity "utilance" gives the ratio between the luminous flux received by a certain reference surface and the sum of the individual output fluxes of the luminaires of the lighting installation. Thus, the larger this ratio, the higher the overall efficiency of the lighting system. Note that for horticultural applications, it is common to use photon-based instead of photometric quantities. Hence, with the standardized definition of utilance referring only to the latter, a new photon-based utilance measure η_{u} is introduced in this work. The corresponding equation reads

$$\eta_{\mathrm{u}} = \frac{\phi_{\mathrm{p,u}}}{\sum \phi_{\mathrm{p}}}, \tag{1}$$

where $\phi_{\mathrm{p,u}}$ is the photon flux received by the reference surface and $\sum \phi_{\mathrm{p}}$ is the sum of photon fluxes emitted by the luminaires of the lighting system.

For a typical indoor lighting application, the reference surface could for example be the working area defined by an office desk. In case of horticultural lighting, though, the most suitable choice for the reference surface is the area covered by the plant leaves, which will also be denoted as usable area (UA) in the following. During the seedling stage, the relevant leaf area covers only a small percentage of the cultivating area, but it continuously increases over time throughout the various growth phases, which therefore results in a progressive expansion of the UA. Thus, assuming a fixed non-adaptable lighting installation illuminating the entire cultivating area, which is usually the standard for existing commercial indoor farms, utilance and consequently the overall system efficiency are quite low during the seedling stage and initial growth phases. With the expansion of the leaf area over time, both the utilance and the overall system efficiency naturally increase—but still in a non-optimal manner. If, on the other hand, a lighting system is used that is capable of adapting its light distribution to match the leaf surface area at any stage of plant growth, which will minimize the wasting of optical radiation without the need of adjusting the distance between plants and luminaires, an optimal system efficiency can be achieved. To get an overview of previous approaches, the following section summarizes the existing work on such targeted horticultural lighting solutions that can be found in the literature.

2.2. Previous Work on Targeted Horticultural Lighting

In 2014, Poulet et al. [27] proposed a novel luminaire setup for horticultural lighting intended to reach higher efficiencies in lettuce growth for future human missions to Mars and other long-distant space destinations requiring bioregenerative life-support systems. For this purpose, they used four identical custom-made LED arrays consisting of individually addressable red ($\lambda_{\max} = 630\,\mathrm{nm}$) and blue ($\lambda_{\max} = 455\,\mathrm{nm}$) LEDs that were arranged in a two-by-two layout for the illumination of a dedicated growth chamber. As part of their conducted growth experiments, they compared the energy-biomass conversion efficiency of a targeted lighting strategy to the efficiency of a traditional full-coverage lighting. While for the latter, all LEDs were energized during the photoperiod of a crop production cycle, the former strategy, by manual adjustment, aimed at energizing only those LEDs that were located directly above individual lettuce heads, i.e., for the targeted lighting strategy, the LEDs were turned on relative to plant position and changing plant size pre-determined by visual estimation.

After 21 days of plant growth, in which the same lighting schedule of increasing photosynthetic photon flux density (PPFD) at leaf level (see Figure 7 of Poulet et al. [27]) was applied for all test conditions, a total number of 16 test lettuces were harvested in each case to compare their corresponding dry weights and calculate the respective energy-biomass conversion efficiencies obtained for the different lighting strategies. It was found that the conversion efficiency of the targeted lighting strategy was almost twice as large as the efficiency determined for the full-coverage method (1.61 vs. $0.86\,\mathrm{g\,kW^{-1}\,h^{-1}}$), where the total energy consumption of the former was less than half of the latter (9.6 kW h vs. 26.6 kW h). However, even though the conversion efficiency could significantly be increased by the targeted lighting approach, there was no positive effect on the total amount of produced edible biomass. On the contrary, the full-coverage treatment results in a considerably larger edible dry weight of 18.06 g compared to only 13.59 g obtained for its targeted counterpart. As discussed by Poulet et al. [27], this difference in terms of dry weight can be explained by the additional amount of "wasted" light getting reflected from the polystyrene growth surface used for crop spacing onto nearby plant leaves, which eventually increased the total number of absorbed photons and lead to the approximately 25 % higher crop productivity for the full-coverage compared to the targeted lighting strategy, where only a negligibly small amount of light fell onto and got reflected from the surface area between neighboring plants. At the same time, though, significantly less light was wasted. In summary, Poulet et al. [27] stated that, despite the observed slight reduction in productivity, targeted lighting strategies in general are capable of enhancing energy savings and provide an appropriate and sustainable approach for modern crop cultivation.

A similar, yet different approach for targeted horticultural lighting was discussed by Li et al. [28], who used a zoom lens setup to adjust the emitted light distribution of the lighting system to precisely illuminate the plants' canopy area. Their custom-made lighting system comprised 16 multi-chip LEDs, each of which was equipped with a convex lens and consisted of two red LED chips ($\lambda_{max} = 630$ nm) and a single blue LED chip ($\lambda_{max} = 460$ nm). The combined LED-lens units were arranged in a four-by-four array, where each LED entity was located right above an individual plant seedling (butterhead lettuce) at a distance of 30 cm. An array of 16 Fresnel lenses fixed in a horizontal plane frame structure was mounted directly below the multi-chip LED array and could be manually moved up and down along the vertical direction to change the sizes of the illumination spots on the cultivation board in order to adapt them to match the dimensions of the plant canopy at each growth stage. Corresponding growth curves were recorded over the course of a 25 days growth period after which the test plants were harvested to measure relevant growth parameters. A second, full-coverage setup was used as the corresponding control condition, where the illumination was provided by a conventional LED arrangement of four custom-made panels of red ($\lambda_{max} = 630$ nm) and blue ($\lambda_{max} = 460$ nm) LEDs placed at a horizontal distance of 30 cm above the seedlings. In both cases, the same lighting scheme of increasing PPFD levels was applied using a fixed 8:1 red-vs-blue ratio (for further details see "Light Treatments" section of Li et al. [28]). Comparing both illumination strategies, it was found that the targeted zoom lens setup saved more than 52 % of the electrical energy that was required for the full-coverage treatment (23.73 vs. 49.51 kW h m^{-2}), which resulted in a 55.6 % larger overall biomass conversion efficiency for the former in comparison to the latter (94.38 vs. 60.64 g kW^{-1} h^{-1}). However, similar to the findings of Poulet et al. [27], there was again a significant decrease in absolute fresh (dry) leaf weight from 45.23 ± 5.69 g (1.89 ± 0.45 g) for the full-coverage treatment to 37.68 ± 2.04 g (1.31 ± 0.21 g) for the targeted zoom lens solution, which was complemented by a reduction in the corresponding photosynthesis activity. Li et al. argued that the enhanced photosynthesis and the higher yield in plant growth obtained for the full-coverage treatment might be a result of the observed higher temperatures of the growth environment [30–32] in combination with a smaller leaf temperature leading to the formation of thicker leaves [33] due to an increased transpiration rate [34,35] and, thus, a better leaf cooling.

Despite the observed reduction of the absolute yield in plant growth, the study results of Poulet et al. and Li et al. both confirmed that, in contrast to conventional lighting strategies, higher efficiencies are achievable by applying targeted setups. Even though the reported dry weights decreased by 25% and 30% when comparing the corresponding yields obtained for targeted versus conventional lighting, the former clearly outperformed the latter in terms of biomass conversion efficiency, where an increase of 46.6% and 55.6% could be observed in both studies. Thus, from the valid comparisons of both lighting strategies performed by Poulet et al. and Li et al., it must be concluded that targeted lighting provides an excellent alternative for the overall improvement of lighting efficiencies and energy savings, especially with regard to vertical indoor farming applications. However, so far, the existing targeted lighting strategies still require manual adjustments that demand for an additional (daily) human interaction and, consequently, appear unsuitable for large-scale implementations. To overcome this drawback, the present work proposes a novel, fully-automated approach that, by making use of a specifically designed luminaire with object detection capabilities, automatically adapts the emitted light distribution to comply with the canopy area at each stage of plant growth without the need for further intervention on behalf of the operator.

2.3. System Design

An overview of the different system components is given in Figure 1. Each luminaire of the scalable lighting system consists of a certain number of LED segments in an annular arrangement that can be controlled individually via suitable LED drivers to vary the corresponding light distribution. A so-called reference luminaire is used to detect and measure the canopy area and crop size during the growth phase. For this purpose, it is equipped with an 8-megapixel RGB Raspberry Pi camera (Camera Module 2, Raspberry Pi Foundation, Cambridge, UK), whose captured images are analyzed in real-time using dedicated software running on a Raspberry Pi micro-computer (Raspberry Pi 3 Model B+, Raspberry Pi Foundation, Cambridge, UK). From this analysis, the crop size at each growth stage is determined so that the LED segments can be adjusted accordingly to adapt the luminaires' light distributions to match the crops' canopy area as good as possible. Each luminaire is mounted at a height of 0.4 m above the cultivation board resulting in a mean PPFD at leaf level of 200 µmol m^{-2} s^{-1}. A more detailed discussion on the different system components is provided as part of the following subsections.

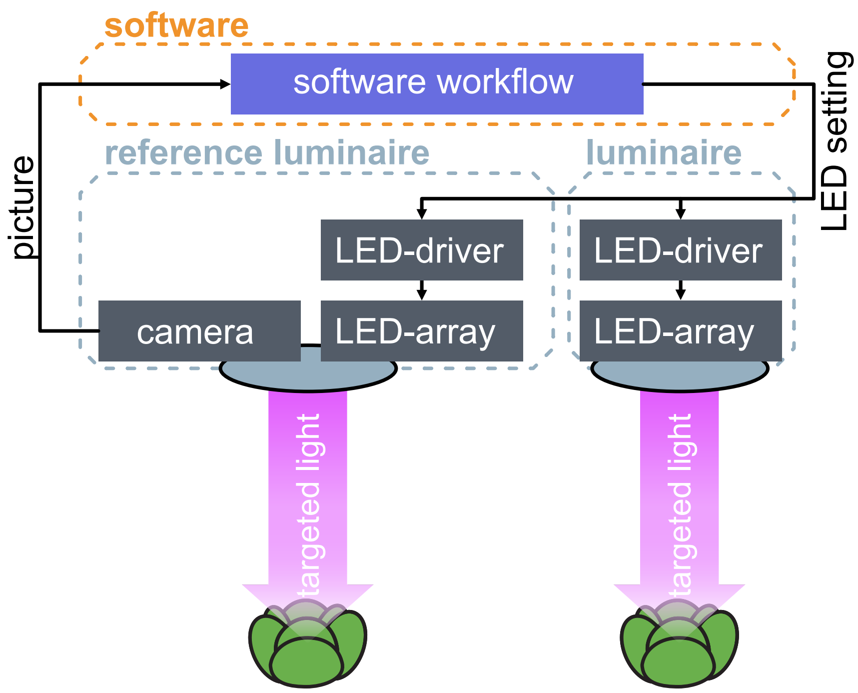

Figure 1. Overview of the proposed horticultural lighting system indicating the different system components and their interactions.

2.3.1. Number and Size of Illumination Segments

When viewed from above, the canopy surface areas of growing crops such as lettuce can be approximated by circles of changing diameter. To adapt the luminaires' light distributions to match these UAs as good as possible, it therefore seems expedient to combine their individual LED segments in an annular arrangement of changing diameter, too. Ideally, an infinite number of LED segments would allow for a precise adjustment of the resulting illumination spots to be in accordance with the UAs throughout all growth stages. However, for real-world applications, a trade-off must be found between the luminaires' complexity and the potential energy savings in comparison to a full-coverage lighting strategy.

In order to find such an optimal trade-off LED configuration, a clear distinction should be made in the following between "LED segments" on the one hand and "illumination segments" on the other hand. Whereas the former is a feature of the luminaire and, as indicated above, denotes the annular arrangement of LEDs that belong together by being connected in series (see Section 2.3.2), the latter denotes the correspondingly illuminated areas on the cultivation surface and, thus, defines the relevant UAs. To find an adequate set of illumination segments in terms of their number and sizes, lettuce growth data taken from Li et al. [28] are used for optimization. Based on the corresponding results, an optimal luminaire LED configuration can eventually be determined. As the optimization criterion, a photon loss function, which gives the number of photons N_{loss} that do not hit the plant leaves, can be defined accordingly and is given by:

$$N_{\mathrm{loss}} = \int_{t_{\mathrm{seed}}}^{t_{\mathrm{harvest}}} E_{\mathrm{p,mean}} \cdot (A_{\mathrm{spot}}(t) - A_{\mathrm{leaf}}(t))\mathrm{d}t, \tag{2}$$

where $E_{\mathrm{p,mean}}$ is the mean photon flux density, A_{spot} is the spot area of the illumination, A_{leaf} is the projected plant leaf area (i.e., the UA), and $[t_{\mathrm{seed}}, t_{\mathrm{harvest}}]$ is the time interval that has elapsed from planting the seedlings to harvesting the grown crops.

In the work of Li et al. [28], lettuce growth data were collected once a day over a 24 days period so that the integral of Equation (2) translates to a summation of the form

$$N_{\mathrm{loss}} = E_{\mathrm{p,mean}} \cdot \pi \sum_{t=1}^{24} \cdot (r_{\mathrm{spot}}^2(t) - r_{\mathrm{leaf}}^2(t)), \tag{3}$$

where r_{spot} and r_{leaf} denote the radii of the illumination spot and the lettuce leaf area, respectively. For this calculation, the growth curve of lettuce determined by Li et al. [28] is used as $r_{\mathrm{leaf}}(t)$. Note that in the present case the latter is approximated by the maximal leaf length observed for the specific growth stage. The radius of the illumination spot, on the other hand, is constrained to be always equal or larger than the maximal leaf length value. The relative energy savings in comparison to full-coverage lighting denoted by ζ is then given by

$$\zeta = 1 - \frac{N_{\mathrm{loss}}}{N_{\mathrm{coverage}}}, \tag{4}$$

where N_{coverage} is the number of photons required for a full-coverage treatment, which can be estimated from Equation (3) by setting $r_{\mathrm{spot}}(t)$ to 150 mm (based on the maximal lettuce leaf length observed from Li et al.'s growth experiments) and $r_{\mathrm{leaf}}(t)$ to 0. Equation (4) eventually needs to be maximized by finding an optimal illumination segment configuration. Using Python, the potential energy savings were analyzed for different arrangements of 1 to 5 illumination segments. In each case, the illumination segments' radii were varied between 24 mm and 150 mm in 1 mm increments to calculate all possible combinations. It was further assumed that all photons created by the luminaire's LED segments are received by the corresponding illumation segments on the cultivation surface so that the optimization can be performed in a technologically independent manner, i.e., no information on the directional emission characteristics of the LED segments was required to estimate the maximal potential energy savings compared to full-coverage lighting. The most efficient combinations of segment radii for different numbers of illumination segments are finally summarized in Table 1.

Table 1. Relative energy savings in comparison to full-coverage lighting for different illumination segment configurations on the cultivation surface. The relative savings were calculated by assuming that all photons created by the luminaire's LED segments are received by the corresponding illumination segments on the cultivation surface.

# of Segments	Segment Number, Optimal Radius in mm					Relative Savings in %
	1	2	3	4	5	
two	92	150	-	-	-	60.1
three	62	116	150	-	-	79
four	53	92	119	150	-	87.6
five	41	62	92	119	150	90.9

Figure 2 correspondingly depicts the relative maximal energy savings as a function of the number of illumination segments. It can be seen that for more than three illumination segments, the increase in energy savings flattens considerably. Thus, as a trade-off between the luminaires' complexity and the expected energy savings potentials, using three illumination segments of 62 mm, 116 mm and 150 mm appears to be an adequate choice for achieving sufficiently good system performance while still keeping its architectural demands to a manageable level. Finally, it should be noted that, considering real-world setups, different LED emission characteristics and arrangements of course change the amount of photons received by each of the so-determined illumination segments or relevant UAs, leading in general to deviating and slightly reduced degrees of energy savings in practice. However, extensive pre-tests and simulations with different emission characteristics and LED arrangements during the development of the luminaire prototype have revealed that the overall best results in terms of UA coverage can be achieved for the proposed optical design and system components outlined in the following sections.

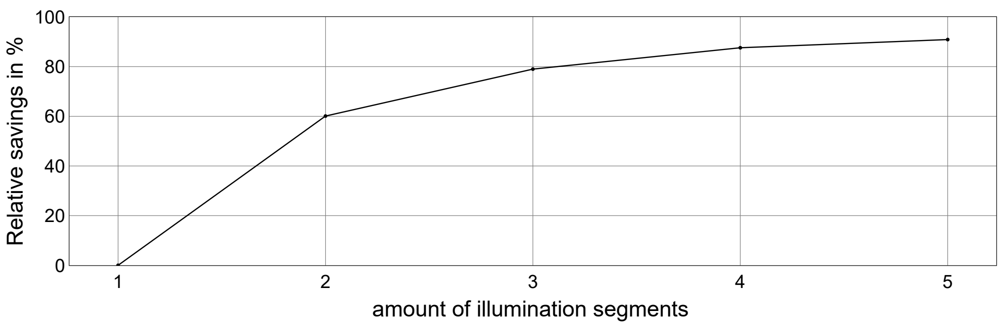

Figure 2. Relative maximal energy savings by using targeted lighting in comparison to full-coverage treatment as a function of illumination segments.

2.3.2. LED Segments

The annular LED segments, as a key feature of the proposed horticultural luminaire, represent individually addressable luminaire elements that are intended to provide a targeted illumination for crop cultivation by providing photons to the previously determined adequate set of illumination segments defining the relevant UAs. The corresponding LED segments can be dimmed separately so that the resulting photon flux densities can be adjusted accordingly and harmonized between different UAs. For this purpose, each LED segment comprises a certain number of white mid-power LEDs of the LUXEON SunPlus 2835 Line (Lumileds, Amsterdam, The Netherlands) that were connected in series. Their arrangement on a custom-designed printed circuit board (PCB), which also serves as the luminaire's heat sink, is illustrated in Figure 3a. Integrated LED driver electronics (MAX16822A, with the recommended peripheral components) ensure direct control of the LED segments via a microcomputer, i.e., a Raspberry Pi, without the need for a separate wire-connected driver component. The reference luminaire further provides an additional camera mount close to the center of its PCB. This mount can hold a small Raspberry Pi camera module for taking time-resolved images of the growing plants' canopy surface area for an automatic crop size detection (see Section 2.5).

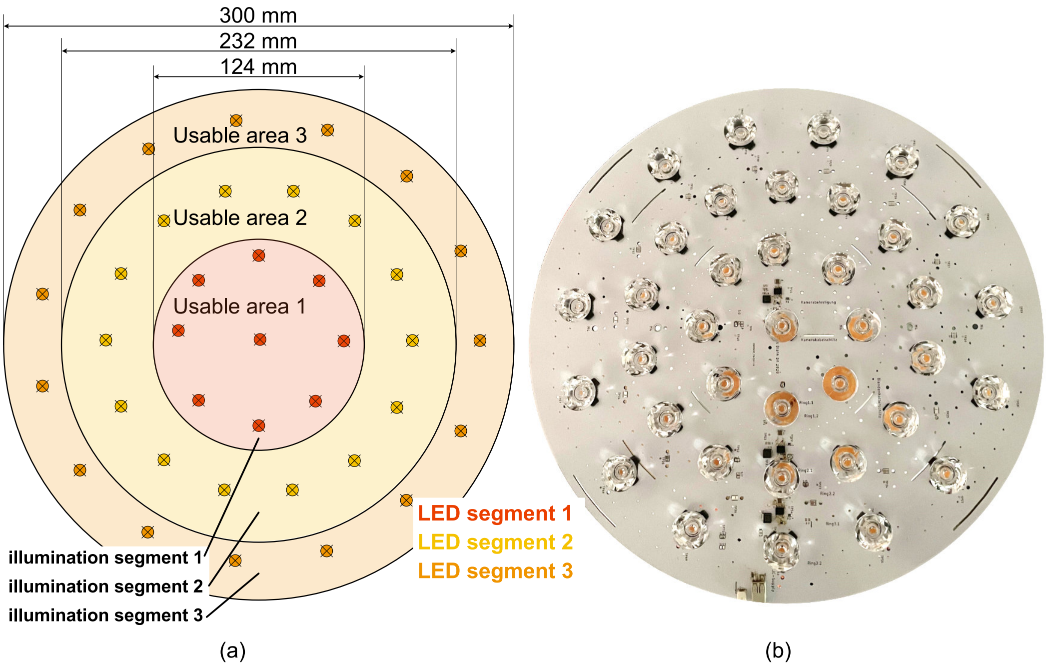

Figure 3. (**a**) Overview of the arrangement of the test luminaire's illumination segments/relevant UAs and LED segments. LEDs of the same color are connected in series. (**b**) Picture of the real luminaire's pcb.

Regarding the luminaire's spectral design aspects, the selected LEDs show distinct peaks at 450 nm and 650 nm of their emitted light spectrum to increase the overall PPFD and, thus, are specifically tailored for horticultural applications. The relative spectral radiance distribution of the used LEDs is given in Figure 4.

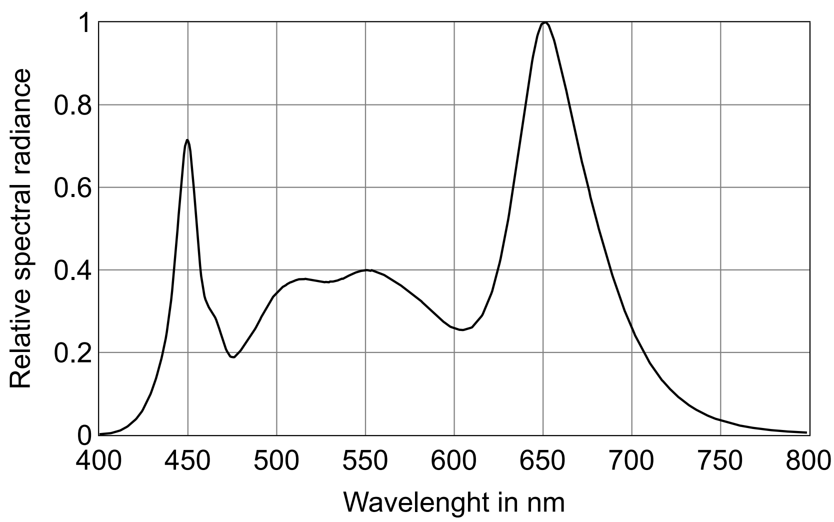

Figure 4. Relative spectral radiance distribution of the used LUXEON SunPlus 2835 LEDs.

Note that using only one type of LEDs additionally ensures spectral homogeneity on illuminated surfaces. To further increase utilance and system efficiency, each LED is equipped with a HEIDI-RS total internal reflection lens (LEDil Oy, Salo, Finland) with a beam angle of 8°, see Figure 3b. This helps to reduce the overall photon loss by shaping the luminaire's light emission to achieve a sharply delineated illumination of the UAs so that less photons get wasted because of a too broad and diffuse light distribution.

2.4. Metrics to Quantify Homogeneity of the PPFD Distribution

Using the proposed LED-lens combinations might lead to an increase of light spots in the different UAs. Several uniformity metrics are therefore introduced to quantify the corresponding illumination homogeneity in order to confirm the suitability of the proposed approach in terms of ensuring an even crop growth.

According to CIE S 008/E-2001 [36], the uniformity measure u_1 is defined as the ratio of the minimum to the average value of the illuminance measured horizontally on a reference surface. Because of the intended use of photon-based instead of photometric quantities as part of the present work, u_1 is re-formulated accordingly to represent the ratio between the minimum $E_{\text{p,min}}$ and the average $E_{\text{p,mean}}$ PPFD values:

$$u_1 = \frac{E_{\text{p,min}}}{E_{\text{p,mean}}}. \tag{5}$$

Similarly, u_2 can be re-defined as the ratio between $E_{\text{p,min}}$ and the maximum PPFD value $E_{\text{p,max}}$, representing a measure for the span of the corresponding PPFD distribution. The corresponding equation reads

$$u_2 = \frac{E_{\text{p,min}}}{E_{\text{p,max}}}. \tag{6}$$

When applying Equations (5) and (6), the lowest PPFD values are expected to be found close to the edges between individual UAs. These specific boundary regions, however, are less relevant for an even plant growth since, by definition, the UAs are typically larger than the plant's canopy surface area at each growth stage (only negligibly small portions of the plant might temporarily extend a UA's boundary before the next LED segment is turned on by the algorithm discussed in Section 2.5). Hence, in order to provide a more accurate indication of potential non-uniformities within the relevant areas, a more suitable metric should be introduced that evaluates homogeneity by relating the fractional area in which the PPFD lies within a specific range around the desired PPFD value for an optimal lettuce growth (i.e., 200 μmol m^{-2} s^{-1}) to the total area A_{total} of the respective UA. The so-defined uniformity measures $u_{10\%}$ and $u_{20\%}$ are thus given by

$$u_{10\%} = \frac{A_{\text{bet.180..220}}(E_P(x,y))}{A_{\text{total}}}, \text{ where } 180\,\frac{\mu\text{mol}}{\text{m}^2\,\text{s}} < E_p(x,y) < 220\,\frac{\mu\text{mol}}{\text{m}^2\,\text{s}}, \tag{7}$$

$$u_{20\%} = \frac{A_{\text{bet.160..240}}(E_P(x,y))}{A_{\text{total}}}, \text{ where } 160\,\frac{\mu\text{mol}}{\text{m}^2\,\text{s}} < E_p(x,y) < 240\,\frac{\mu\text{mol}}{\text{m}^2\,\text{s}}, \tag{8}$$

where $A_{\text{bet.180..220}}$ and $A_{\text{bet.160..240}}$ are the areas for which the corresponding PPFD distribution $E_p(x,y)$ deviates from the desired value by less than 10 % and 20 %, respectively.

2.5. Automated Crop Size Detection and Lighting Adjustment

Each LED segment can be dimmed separately to adapt the luminaire's overall light distribution to the crops' current growth stage. In order for the lighting system to do this automatically and without the need for additional human intervention, the diameter of the canopy surface area must be determined first by using the Raspberry Pi camera module which is mounted to the system's reference luminaire and programmed to take a corresponding image every hour. Based on this periodic image acquisition, an appropriate color detection algorithm can be used to determine the crop diameter in a time-resolved manner. If the observed crop diameter is larger than the area illuminated by an inner LED segment, the next outer LED segment will be switch on, too. The Raspberry Pi is not only used to capture and analyze the crop images but also to control the corresponding LED driver electronics and, thus, the PPFD on the plant canopy by using dedicated pulse-width modulated (PWM) signals to drive the individual LED segments.

To determine the actual crop size, a real-time green-pixel analysis is performed using Python and the OpenCV library. Figure 5 illustrates the corresponding workflow. First, the original picture as obtained from the Raspberry Pi camera module is converted from RGB to HSV color space since the latter is most suitable for pixel selection based on hue values [37,38]. A green hue filter is then applied to determine the number of pixels of leaf content within the range of each of the different UAs. If, for example, more than 10 % of the pixels assigned to the second UA are found to be green, i.e., the corresponding crop leaf area is expected to have a diameter larger than the area that can be illuminated by the inner LED segment alone, the middle LED segment of the luminaire will additionally be switched on. The same holds true if a continuing crop growth results in more than 10 % of the pixels belonging to the third UA to be registered as green. In this case, all three LED segments will be energized, complying with a full-coverage lighting. Here, the 10 % threshold was determined empirically in a series of pre-tests during system development. It basically represents a good compromise between system sensitivity and the need, for energy saving reasons, to avoid switching on the next LED segment too early as long as only a small portion of the plant leaves extends the current UA. Moreover, it should be noted that the PWM signals that control the intensity of the different LED segments via the LED driver electronics are defined by corresponding code values stored in a dedicated look-up table and vary with the number of illuminated UAs. The code values were initially determined during the calibration process of the luminaire intended to provide a homogeneous illumination at a target PPFD of 200 µmol m^{-2} s^{-1} for each of the different UA settings, see Section 3.1.

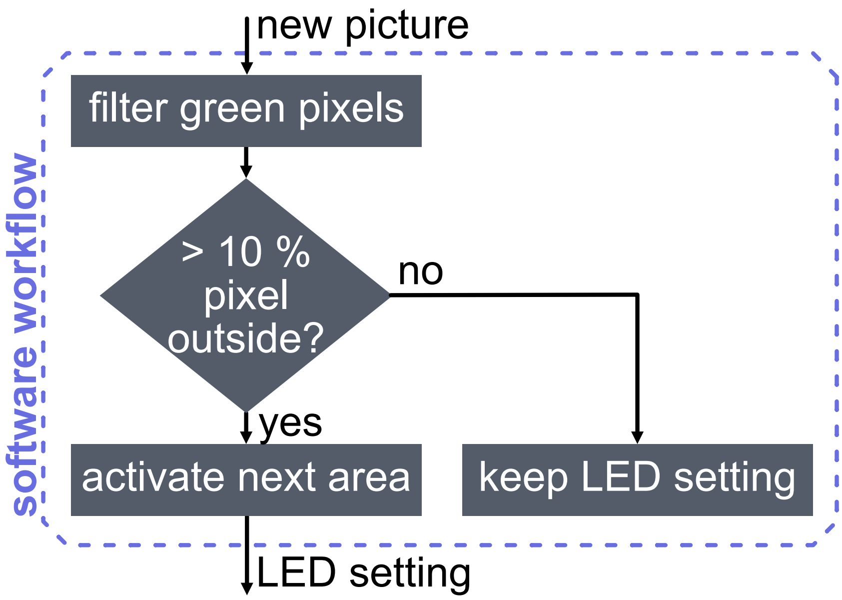

Figure 5. Workflow to determine the crop diameter for automated LED control. If more than 10% of the green pixels are outside the current UA which is illuminated by a certain LED segment, the next LED segment will additionally be switched on to increase the size of the illumination spot accordingly.

Obviously, the proposed lighting system uses only a single reference luminaire to extract the required plant growth parameters from image acquisition. The assumption that underlies this system design aspect is that crops of the same species sowed at the same time and grown under the same conditions can be expected to show a similar growth behavior and, in particular, yield similar diameters. Thus, using a single reference/master luminaire appears to be sufficient for controlling the whole network of slave luminaires. Nonetheless, extending the lighting system by individually controlled luminaires is straightforward and might yield some further energy savings in case of an unequal plant growth.

3. Results

3.1. Uniformity Analysis

Luminance image captures of the different light settings are taken to analyze the uniformity and size of the illuminated areas as provided by the proposed horticultural luminaire. As each of the three LED segments can be dimmed individually, the dimming values are varied until the highest uniformity is reached. A sheet of white paper with printed diameters of the different relevant UAs is placed below the reference luminaire at a distance of 40 cm and aligned accordingly. Measurements were performed using a TechnoTeam LMK-5 luminance camera (TechnoTeam Bildverarbeitung GmbH, Ilmenau, Germany) positioned at a 0°/45° measurement geometry. The sheet of paper is assumed to have a Lambertian reflection characteristics [39,40]. Additional reference measurements of the resulting PPFD are performed using a spectral irradiance sensor CSS-45 (Gigahertz Optik GmbH, Türkenfeld, Germany), which is placed onto the reference sheet right in center of the inner UA. Because of the spectral homogeneity of the illuminated areas, luminance and irradiance are proportional to each other so that the pixelwisely measured luminance values can directly be mapped to corresponding PPFD values. This leads to the resulting PPFD distributions shown in Figure 6.

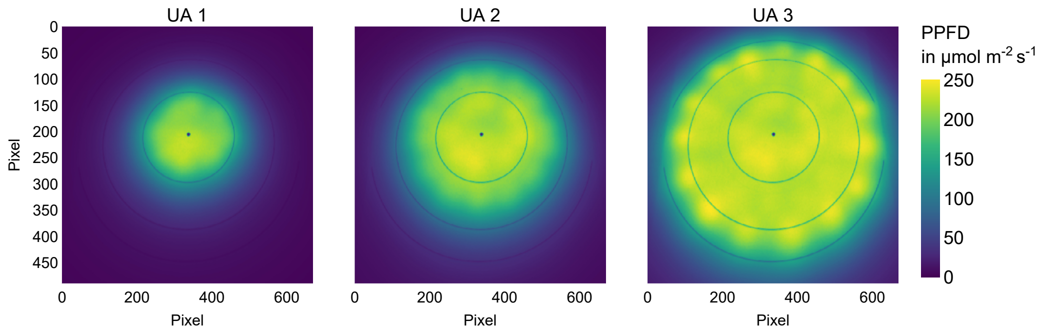

Figure 6. Measured PPFD distributions of the different UAs. Note that x and y coordinates are given in pixels as the optical distortion of the measurement geometry of the used setup prevented a proper assignment of pixel coordinates and their absolute position in metric units. As can be seen, the proposed luminaire prototype configuration shows the desired adaptive UA coverage capabilities.

Based on these results, minimum, maximum, and averaged PPFD values were determined for each of the specific UAs and are summarized in Table 2. As can be seen, the largest measured PPFD value is 252.45 µmol m^{-2} s^{-1} located within UA 3. It is approximately 26 % larger than the target PPFD value of 200 µmol m^{-2} s^{-1}. The lowest PPFD value, on the other hand, is 88.68 µmol m^{-2} s^{-1} and can be identified to be located close to the edge of UA 3, which is expected from the discussions of Section 2.4. The corresponding average PPFD values (i.e., 191.79 µmol m^{-2} s^{-1} for UA 1, 180.7 µmol m^{-2} s^{-1} for UA 2, and 215.69 µmol m^{-2} s^{-1} for UA 3) are all within a 10 % range deviating from the target PPFD value.

Table 2. Uniformity comparison of the different UAs. E_p values in µmol m^{-2} s^{-1}.

	$u_{10\%}$	$u_{20\%}$	u_1	u_2	$E_{p,min}$	$E_{p,max}$	$E_{p,mean}$
UA 1	0.58	0.9	0.69	0.57	131.58	231.76	191.79
UA 2	0.38	0.7	0.49	0.36	88.68	243.57	180.7
UA 3	0.23	0.92	0.61	0.52	131.16	252.45	215.69

Regarding the considerations of uniformity, it must be stated that UA 2 shows the smallest metric values with 0.49 and 0.36 for u_1 and u_2, respectively. These findings can be explained by the low PPFD values found near the boundary to UA 3 when only the two inner LED segments are lit, see Figure 6. For both UA 1 and UA 3, similar and slightly larger metric values are observed. While UA 1 shows values of 0.69 for u_1 and of 0.57 for u_2, values of 0.61 and 0.52, respectively, must be reported for UA 3.

Because of the strong impact of the lower PPFD values close to the boundaries between adjacent UAs, a more reliable estimate of uniformity that is less susceptible to these kind of "outliers" was needed. In particular, since potential effects of resulting inhomogeneities can easily be avoided in practice by increasing the system sensitivity in such a way that the next LED segments are already switch on at an earlier growth stage for a smoother transition but at the costs of reduced energy savings, see Section 2.5. Hence, for providing more suitable homogeneity metrics that better reflect the relevant UA contributions, the ratios $u_{10\,\%}$ and $u_{20\,\%}$ have been introduced in Section 2.4. $u_{10\,\%}$ shows values of 0.58 for UA 1, 0.38 for UA 2 and 0.23 for UA 3, indicating that in the worst case of UA 3, only about a fifth to a fourth of the illuminated area shows PPFD values deviating less than 10 % from the target value of 200 µmol m^{-2} s^{-1}. However, as can be seen when looking at the $u_{20\,\%}$ metric calculations, considerably larger fractions of the UAs show PPFD values that deviate less than 20 % from this target value. Compared to UA 2, which shows a value of $u_{20\%} = 0.7$, both UA 1 and UA 3 yield a slightly higher uniformity of 0.9 and 0.92, respectively. In order to reach an approximately equal uniformity $u_{20\,\%}$ of 0.9 in all three UAs, the radius of UA 2 needs to be reduced to 100 mm. However, changing the diameter of UA 2 accordingly also leads to a decrease in the potential power savings from 79 % to 73 %, when applying Equation (4). Thus, the current selection of UA diameters seems to provide a good balance between energy savings and homogeneity of the illumination, in particular since the proposed luminaire prototype configuration shows the desired adaptive UA coverage capabilities as emphasized by the corresponding PPFD distributions of Figure 6.

3.2. Calculation of Utilance

The determination of utilance was performed by using the light simulation software LightTools (Synopsys, Inc., Mountain View, CA, USA). Luminous intensity distribution curves provided by the lens manufacturer for the LED-lens combination using the standardized photometric format of the Illuminating Engineering Society (IES format) were used for an accurate modelling of the light emission characteristics of the luminaire system. The assumed mounting height above the cultivation area was 40 cm, where again the same three annular evaluation areas (diameters of 62 mm, 116 mm and 150 mm) as in Section 3.1 were used to define representative UAs. Corresponding utilance values were then calculated by adopting Equation (1). Results are summarized in the first column of Table 3. As can be seen, the lowest utilance is obtained for UA 1 with only 59 % of the emitted photons being allocatable to this area. UA 2 and UA 3, on the other hand, show considerably higher utilance values of 81 % and 83.05 %, respectively.

Table 3. Calculated utilance.

	$\eta_{U_{\text{target}}}$	$\eta_{U_{\text{total}}}$
UA 1	0.59	0.22
UA 2	0.81	0.63
UA 3	0.83	0.83

For a better comparison, utilance values as obtained for a full-coverage lighting strategy using the same luminaire (i.e., all LED segments constantly turned on) are also provided and given in the second column of Table 3. Again utilance is calculated for the three different UAs. It should be noted that the values for UA 3 are the same for both targeted and full-coverage lighting. This basically represents the fact that the former converges against the latter as further LED segments are energized due to the progressing plant growth. Significantly enhanced utilance, on the other hand, can be reported for the targeted lighting strategy when considering the earlier growth stages, i.e., for UA 1 and UA 2. In addition, less fluctuation between the different UAs is observed in this case, which indicates that the utilance is less dependent on the growth stage for targeted compared to full-coverage lighting.

3.3. Calculation of Electrical Power Consumption for One Head of Lettuce (kWh)

Using the growth data $r_{\text{lettuce}}(t)$ reported by Li et al. [28], the electrical energy consumption for the production of a single head of lettuce is calculated when applying targeted versus full-coverage lighting using the test luminaire. For this purpose, the power consumption per UA is calculated from the measured voltage and current of the different LED segments. The corresponding LED driver's efficiency depends on the duty cycle. Hence, for each LED segment the duty cycle is adjusted such that the driver efficiency can be constantly set to 90 %. The resulting formula for calculation the respective electrical energy consumption ($P_{\text{el.}}$) then reads

$$P_{\text{el.}} = 1.11 \cdot \sum_{i=1}^{24} U(i) \cdot I(i) \cdot 16\,\text{h}, \qquad (9)$$

where the factor 1.11 represents the driver's efficiency and $U(i)$ and $I(i)$ are the voltage and current of the active LED segments. Note that the summation index i denotes the ith day of the assumed growth experiment with each active LED segment being constantly turned on for 16 h per day. Using Equation (9) to calculate the total energy consumption for growing a single lettuce head over the period of 24 days eventually gives a value of 3.43 kW h and 7.03 kW h for the targeted and full-coverage lighting strategy, respectively. Thus, targeted lighting consumes less than half of the electrical energy required by the full-coverage approach.

Based on the maximally achievable efficiencies of current and future LED generations, see Kusuma et al. [23], the electrical energy consumption for a targeted lighting strategy applied to grow a single lettuce head is further calculated for an idealized test luminaire with ideal optics and optimal LED driver efficiency. For this purpose, each UA is multiplied with the assumed PPFD of 200 µmol $m^{-2}\,s^{-1}$ and divided by the estimated LED conversion efficiency to create the required input data for re-evaluating Equation (9). Table 4 summarizes the results for various LEDs and LED combinations.

Table 4. Theoretical comparison of electrical energy consumption for different LED efficiencies under the assumption that 100 % of the generated photons reach the UAs.

LED	Efficiency in µmol W^{-1}	Power Consumption per Head of Lettuce in kWh
Horticulture white	2.28	1.33
blue/red current	3	0.92
white/red current	2.78	0.99
blue/red prognosed	4.1	0.67
white/red prognosed	3.4	0.81
450 nm physical maximum	3.76	0.81
660 nm physical maximum	5.52	0.55

3.4. Visualization of the Automated Lighting Adjustment

In order to visualize the system behavior of the proposed test luminaire prototype, a dedicated growth experiment using pre-grown lettuce heads (14 days old) has been performed over a period of 30 days, where the size of the illuminated area has been adjusted automatically depending on the registered leaf surface area. Figure 7 illustrates the respective changes in illumination according to the different growth stages. As can be seen, a good coverage of the leaf surface area can be achieved at all stages while, at the same time, minimizing the amount of wasted photons.

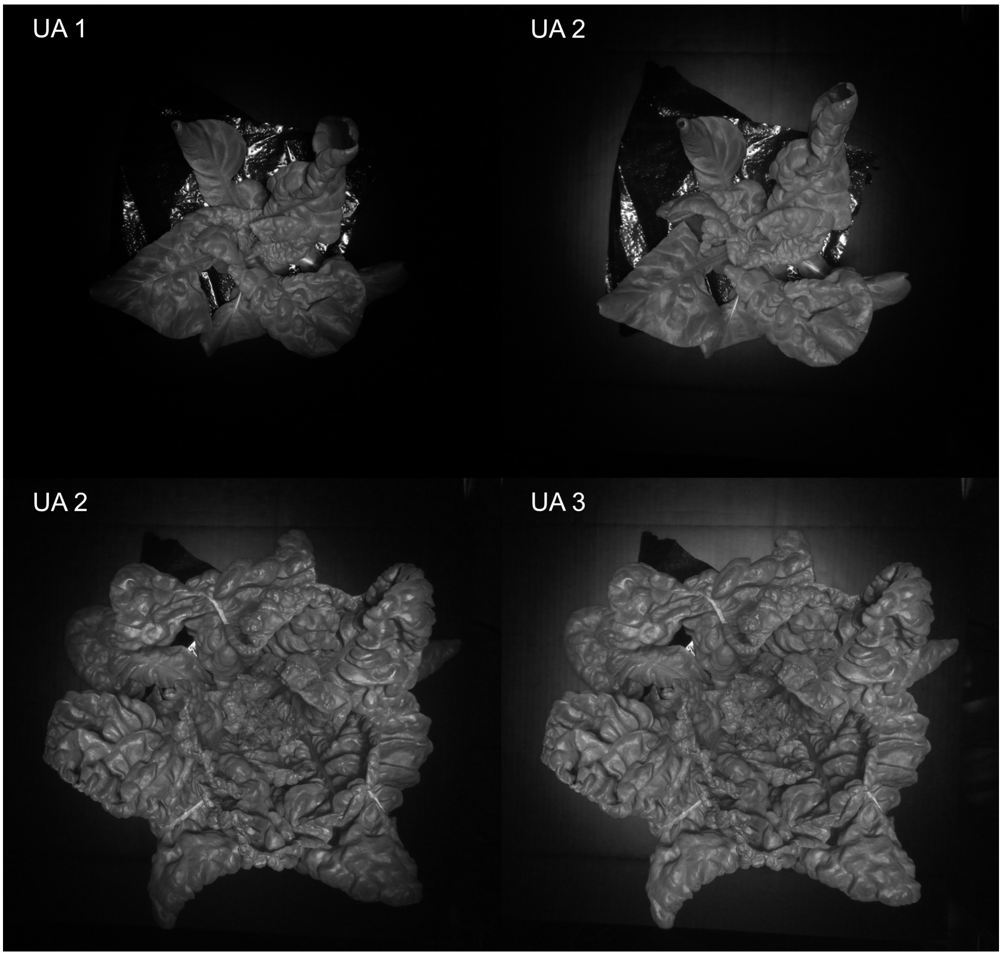

Figure 7. Illuminated UAs in dependence of the size of the crop leaf area. **Upper row**: Transition in illumination from UA 1 to UA 2 due to progressing plant growth. **Lower row**: Transition in illumination from UA 2 to UA 3 due to progressing plant growth.

4. Discussion

In this work, a novel, fully-automated lighting strategy has been proposed to adapt the light distribution of the horticultural luminaire to match the effective leaf surface area at each stage of plant growth in order to minimize the wasting of optical radiation throughout the growing process. A corresponding system prototype has been developed and tested accordingly. It has been shown that the proposed lighting system is capable of properly adjusting its light emission to comply with the canopy surface area by automated crop size detection, which considerably increases the utilance compared to (standard) full-coverage lighting, in particular for the earlier growth stages. In addition, it was found that the targeted approach shows a higher utilance constancy across the different growth phases than its full-coverage counterpart, emphasizing its suitability for great energy savings in horticultural lighting applications. For example, it was found that the proposed targeted lighting strategy is likely to consume less than half of the electrical energy required by full-coverage lighting.

Future work thus addresses the large-scale integration of this promising lighting approach to be able to collect and analyze real data based on comprehensive field studies. The long-term goal is to properly quantify the energy savings in relation to crop yield for a variety of different plants and horticultural scenarios. In this context, it may be expedient to not only consider in a future system iteration the crop diameter but also the plant height in order to keep the PPFD at a constantly optimal level throughout all growth phases. Usually, as the plant continues to grow, its distance to the luminaire gets reduced, which increases the resulting PPFD on the leaf surface area. A corresponding density regulation can for example be realized by dimming the individual LED segments based on the distance obtained from an image-based plant height estimation or by applying an adequate leaf area–plant height model.

With the developed luminaire prototype, it is further possible to customize light distributions in such a way that different intensities are applied to different parts of the plant's canopy surface area. For example, the PPFD in the central regions can be set to a higher value than in the outer parts so that potential effects of these spatial inhomogeneities on the plant growth can be investigated in a systematic manner. In addition, the proposed lighting system shall be further extended by integrating spectrally tunable LEDs that, in combination with the luminaire's spatial flexibility, allow for using different light spectra to illuminate different crop parts to potentially trigger and examine certain grow mechanism affected by changes in the spectral light composition.

Finally, it is of interest to further investigate, and conceivably compensate, the effects of a reduced absolute crop yield for targeted compared to full-coverage lighting due to a reduction of the amount of diffusely reflected lighting components, as discussed in the literature [41]. So far, corresponding experiments to confirm this effect are limited to greenhouses only. Future experiments should therefore focus on indoor cultivation, where lighting conditions are not comparable to those observed for summer greenhouses. In particular, no compensation strategies have been proposed yet.

Author Contributions: Conceptualization, J.B. (Jens Balasus), S.B. and T.H.; Data curation, J.B. (Jens Balasus) and J.B. (Janis Blank); Formal analysis, J.B. (Jens Balasus); Methodology, J.B. (Jens Balasus), S.B. and T.Q.K.; Software, J.B. (Jens Balasus) and J.B. (Janis Blank); Supervision, T.Q.K.; Validation, J.B. (Jens Balasus), J.B. (Janis Blank) and T.H.; Visualization, J.B. (Jens Balasus); Writing—original draft, J.B. (Jens Balasus); Writing—review & editing, J.B. (Jens Balasus), S.B., T.H., J.B. (Janis Blank) and T.Q.K.; All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge support for the publication of this work by the Deutsche Forschungsgemeinschaft (DFG—German Research Foundation) and the Open Access Publishing Fund of Technical University of Darmstadt.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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