Investigation of a Scanning Laser Projector as an Energy-Efficient Light Source in Plant Production

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INTRODUCTION

In a world with a growing world population and a faster growing food demand, food security is becoming more and more important. On the other hand, there is an increasing attention for healthy products, which are produced in a sustainable way. Japan is well known for its electronics industry and this knowledge is applied in high-tech food production. The so-called plant factories aim for producing high-quality crops all year round by artificially controlling the cultivation environment allowing growers to plan production (METI, 2013). Another advantage is that no pesticides are needed in the closed environment, resulting in safe products. The closed artificial-lighted plant factories in Japan are considered to become a significant food supplier in dense-populated areas with little space for agriculture. However, there is a major challenge which averts investors; most plant factories are not profitable due to large production costs. Especially, the energy costs for artificial lighting are high. Watanabe (2009) estimated that in plant factories with high-pressure sodium (HPS) and fluorescent lamps approximately 40% of the total running costs can be attributed to lighting. Light-emitting diodes (LEDs) are recently introduced in the plant factories, because they have higher light conversion efficiencies. The narrow light-emitting spectrum of an LED gives the possibility to focus only on the required light wavelengths, while thermal infrared radiation can be excluded. Furthermore, the distance to the plants can be decreased, allowing more layers in a multi-layer cultivation system, while the cooling capacity can be decreased. However, the energy costs of the LEDs can still be considered high and thus the search for efficient light sources continues.

To decrease the energy costs of a plant factory, the light efficiency should be maximized. The main goal is to reduce the losses of the light energy input. Four areas can be identified where light energy may be lost, namely in light incidence, light absorption, photochemistry and conversion to biomass. First, the light incidence depends on the direction and distribution of the light beams in relation to the locations of the plants. Therefore, the plant coverage area and the lighting area should be matched. The second loss occurs where photons may be absorbed by the photosynthetic pigments, like chlorophyll, depending on the photon’s wavelength and the absorption spectra of the photosynthetic pigment. The range of 400 to 700 nanometers is most effective for photosynthesis and is called the photosynthetically active radiation (PAR). Third, the processing time of photons by the photosystems are slower than...
the absorption times. Photons can be absorbed in the order of a femtosecond (Blankenship, 2002), while the limiting carbon fixation step takes 5 milliseconds (Nobel, 2009). Figure 1 gives an overview of the different timescales in the photosynthesis process.

A photosynthetic pigment is excited by the absorption of a photon and can stay in this excited state in the pico- to nanosecond (10^-12 s to 10^-9 s) timescale. The absorbed light energy is transferred in the sub-picosecond timescale to another photosynthetic pigment with a lower energy level (Blankenship, 2002). Excess light energy is dissipated through non-photochemical reactions, like fluorescence or heat transmission. In low light levels it is found that 8 photons are required per evolved O2 molecule (Nobel, 2009):

\[
\text{CO}_2 + 2\text{H}_2\text{O} + 8 \text{ photons} \rightarrow \text{CH}_2\text{O} + \text{H}_2\text{O} + \text{O}_2 \quad (1)
\]

Here, \{CH}_2O represents a general carbohydrate, which is ultimately converted into glucose as noted in the general chemical equation of photosynthesis:

\[
6\text{CO}_2 + 12\text{H}_2\text{O} + 48 \text{ photons} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{H}_2\text{O} + 6\text{O}_2 \quad (2)
\]

The fourth and last light energy loss takes place when the chemical stored light energy, in the form of glucose, is not optimally distributed and converted into biomass to facilitate plant growth. This may be considered out of scope when assessing the light energy efficiency.

In this paper, an investigation will be made for using a scanning laser projector for energy-efficient plant illumination. Diode lasers can be very small, can have a high power and there are many possibilities for modulation of the light. Besides, lasers convert electricity very efficiently to light with one wavelength, where unwanted wavelengths and thus thermal radiation can be dismissed completely (Yamazaki et al., 2000). A scanning laser projector has an additional advantage of adapting the lighting to the processing times of the photons.

**MATERIALS AND METHODS**

The possibility of using a scanning laser projector in a plant factory was assessed in two practical experiments using lettuce (Lactuca sativa L. cv. Frillice) seedlings and crops, with similar experimental set-up, measurements and analyses.

**Scanning laser projector**

During the experiments, a Showwx™ laser pico-projector from MicroVision was used as an artificial light source for the plants. A pico-projector is a hand-held electronic device which can display large images. Users can connect it to a media device, like a smartphone, tablet or laptop, to display movies, pictures or presentations at a wall or any object at hand, because the projection is always in focus. MicroVision has developed a miniature projection display technology and given a specific name PicoP. The base is an integrated photonics module scan engine consisting of one red, one green and one blue laser and a micro electro mechanical system (MEMS) scanner. Near each laser output, a lens collects the laser light and composes a very low numerical aperture beam. The three beams are combined into a single beam and sent to the biaxial MEMS scanning mirror. The mirror changes the parallel laser beam to a diverging beam. This beam is scanned in a bidirectional raster pattern (Fig. 2) to minimize the blanking time. The horizontal scan trajectory is a sinusoidal wave, which is driven by the resonant frequency of the wide video graphics array (WVGA) scanner and typically about 18 kHz. The vertical scan motion is a saw-tooth waveform for a fast retrace to the first pixel of a new projection. The vertical velocity depends on the frame rate of the imaging device, typically 60 Hz for an 848 × 480 WVGA resolution (Freeman et al., 2009).

A frame rate \(f_r\) of 60 Hz indicates that 60 images are projected every second, which means it takes 17 ms (\(t_i\)) to scan a complete image. Buckley (2012) described a method to calculate required scanning times to display lines and pixels with a laser projector. The bidirectional scan pattern is given in (Fig. 2), where can be seen that after each displayed line there is a short blanking period. The overscan factor \(k_o\) accounts for the mirror flyback time at the end of the line. This factor depends on the number of vertical lines \(N\) (480 pixels), the frame rate \(f_r\), the horizontal scan frequency \(f_h\) (18 kHz) and a dimensionless parameter \(k_o\), which is 1 for unidirectional scans and 2 for bidirectional scans.

![Fig. 1](image1.png)  
**Fig. 1** Schematic model for the reactions and timescales of the light harvesting and processing in the two photosystems. Image adapted from: (Blankenship, 2002; Nobel, 2009).

![Fig. 2](image2.png)  
**Fig. 2** Bidirectional raster scan (Freeman et al., 2009).
INVESTIGATION OF A SCANNING LASER PROJECTOR

The scan times for center (horizontal line) require a shorter scan time than the pixels at brightness (Buckley, 2012). The pixels in the center of a line must be varied to display pixels with an equal width and is most important. Therefore, the scan times of the pixels are divided over the horizontal scan line. In the projection of an image, the time required to display one line, accounting for overscan, is calculated with (3), where the overscan time \( t_o \) is represented by (4). Here, the vertical scan frequency \( f_v \) is set equal to the system’s frame rate \( f_h \) (Buckley, 2012). This results in a line scan time \( t_l \) of 26 \( \mu \)s, including a 8.7 \( \mu \)s overscan time \( t_o \). After the image is fully scanned, the scanner moves back to the top of the image for the next scan, which requires a retrace time \( t_r \) of 4.2 ms (5). The average pixel scan time \( (\bar{t}_p) \), calculated by dividing the actual line scan time by the number of horizontal pixels \( M \) (848 pixels), is 20 ns (6).

\[
K_o = \frac{N \cdot f_h}{f_v \cdot k_o}
\]

\[
\eta_o = \frac{1}{k_o} - 1
\]

(1)

(2)

The time required to display one line, accounting for overscan, is calculated with (3), where the overscan time \( t_o \) is represented by (4). Here, the vertical scan frequency \( f_v \) is set equal to the system’s frame rate \( f_h \) (Buckley, 2012). This results in a line scan time \( t_l \) of 26 \( \mu \)s, including a 8.7 \( \mu \)s overscan time \( t_o \). After the image is fully scanned, the scanner moves back to the top of the image for the next scan, which requires a retrace time \( t_r \) of 4.2 ms (5). The average pixel scan time \( (\bar{t}_p) \), calculated by dividing the actual line scan time by the number of horizontal pixels \( M \) (848 pixels), is 20 ns (6).

\[
t_l = \frac{1 - \eta_o}{N \cdot f_v}
\]

(3)

\[
t_o = \frac{\eta_o}{N \cdot f_v}
\]

(4)

\[
t_r = t_l - N \cdot t_l
\]

(5)

\[
\bar{t}_p = \frac{t_l - t_o}{M}
\]

(6)

However, the scan time per pixel is not evenly distributed over the horizontal scan line. In the projection of an image for visual purposes an evenly distributed brightness is most important. Therefore, the scan times of the pixels must be varied to display pixels with an equal width and brightness (Buckley, 2012). The pixels in the center of a horizontal line require a shorter scan time than the pixels at the edge. The scan times for center \( (t_c) \) and edge \( (t_e) \) pixels can be calculated using (7) and (8) respectively (Buckley, 2012). The scan time per pixel \( t_i \) varies between 17 ns \( (t_i) \) and 28 ns \( (t_e) \), but is on average 20 ns \( (\bar{t}_p) \).

\[
t_c = \frac{k_o}{\pi \cdot M \cdot f_v}
\]

(7)

\[
t_e = \frac{t_c}{\sqrt{1 - k_o^2}}
\]

(8)

After the illumination of one pixel, there is a dark period of 17 ms (equal to \( t_r \)) for that particular pixel. This means that a pixel is illuminated for only one millionth of the time, while the rest of the period is dark. The laser projector has an overall light to dark ratio of 0.5.

The energy content of a photon depends on its wavelength (9). The energy content of a pulse depends on the maximum continuous wave (CW) output of the laser and the illumination time (10). The pulse of one pixel contains on average 4.0 \( \cdot 10^{-7} \) J, which corresponds to 1.9 \( \cdot 10^{-16} \) mole of photons. For one projection, the energy content is 1.7 \( \cdot 10^{-3} \) J with a total of 7.8 \( \cdot 10^{-9} \) mole of photons. The average or pulsed power is calculated with (11). The pulsed power is half of the CW power. This is consistent with the light to dark ratio of 0.5.

\[
E_{\text{output}} = \frac{h \cdot c}{\lambda}
\]

(9)

\[
E = P_{CW} \cdot t
\]

(10)

\[
P_{\text{pulse}} = E \cdot f
\]

(11)

Photosynthesis is driven by the number of photons rather than the energy. The number of photons within the PAR spectrum, the photosynthetic photon flux (PPF) in \( \mu \)mol s\(^{-1} \), indicates how powerful a light source is. The PPF can be calculated by dividing the power of the light source with the energy content of one mole of photons (12). To determine the effect on the photosynthesis rate, the illuminated area is required. The photosynthetic photon flux density (PPFD) in \( \mu \)mol m\(^{-2}\) s\(^{-1}\) can be calculated using (13).

\[
PPF = \frac{P}{E_{\text{photon}} \cdot N_A}
\]

(12)

\[
PPFD = \frac{PPF}{A_{\text{throwover}}}
\]

(13)

The PPF of the laser projector depends on the properties of the lasers, which were retrieved from the user manual. First, the PPF was calculated for each laser using the pulsed power values (12). To project a white plane, all three lasers (red, green and blue) are active. The total PPF of the scanning laser projector can thus be calculated by summing the PPF values of the three lasers (Table 1).

The density of the PPF (PPFD) can be calculated if the size of the projection is known. The projection size depends on the distance between the projector and the object, which is called the throw distance. For this laser projector, the diagonal of the projection is equal to the throw distance. The aspect ratio of the laser projector (16:9) was used to calculate the width and the height of the projection using the Pythagorean Theorem. Thereafter, the projection area and the PPFD were calculated and both are presented as a

| Color    | Laser type               | \( \lambda \) (nm) | \( P_{CW} \) (mW) | \( P_{pulse} \) (mW) | PPF\(_{pulse} \) (\( \mu \)mol s\(^{-1}\)) |
|----------|--------------------------|---------------------|-------------------|-------------------|---------------------------------|
| Red      | AlGaInP laser diode      | 642                 | 90                | 45                | 0.24                           |
| Green    | Frequency doubled IR laser diode | 532          | 60                | 30                | 0.13                           |
| Blue     | GaN laser diode          | 442                 | 50                | 25                | 0.09                           |
| White    |                          | 200                 | 100               |                   | 0.47                           |

Table 1 Laser properties on the Showwx™ laser pico-projector.
function of the throw distance in Fig. 3. There is a trade-off between the projection area and the PPFD: the projection area increases with an increasing throw distance, while the PPFD decreases.

**Experimental set-up**

The experiments were conducted in a clean room with a temperature of 22°C and a relative humidity of 50%. Two air pumps provided oxygen in a water tub, which was filled with a nutrient solution with an initial electrical conductivity (EC) of 2 mS cm⁻¹. Plant plugs were placed into a polystyrene board which floated in the water tub. Two light sources were used: the MicroVision’s Showwx™ laser pico-projector (2.2 W Power consumption) and a TBL-08/5N fluorescent lamp (8 W Power consumption) as a reference light source. The scanning laser projector was mounted at a height where the projection area was sufficient to illuminate all plants. The rectangular size of the projection was about 0.15 m × 0.08 m. The PPFD was measured at plant height and after, the fluorescent lamp was mounted at a height to provide the same PPFD as the laser projector.

**Growth of seedlings**

In the first experiment, the growth of lettuce (*L. sativa* L. cv. Frillice) seedlings was followed. The number of plants and lighting conditions are listed in Table 2. The lettuce seedlings were previously grown for 1 week in a controlled growth chamber using fluorescent light (PPFD of 130 μmol m⁻² s⁻¹) with a set temperature of 22°C, while there was no control for humidity and carbon dioxide.

**Growth of crops**

In the second experiment, the growth of bigger lettuce (*L. sativa* L. cv. Frillice) crops was investigated. The number of plants and lighting conditions are listed in Table 2. These crops had been grown for 1 week in a growth chamber (fluorescent light with a PPFD of 130 μmol m⁻² s⁻¹ and temperature of 22°C) to become seedlings and thereafter for 3 weeks in a larger clean room (fluorescent light of 305 μmol m⁻² s⁻¹, temperature of 22°C, relative humidity of 50% and CO₂ concentration of 1000 ppm).

**Measurements and analyses**

In the two experiments, the lettuce plants (including the polystyrene board) were weighed on a daily basis per light source. The plant temperature was measured on one of the leaves with an infrared thermometer. Also, top-view pictures were taken to monitor visual differences. At the end of the experiments, the fresh weight of each plant was measured. The weight differences were converted to relative growth rates per day to compensate for any initial differences in size. A statistical analysis (ANOVA) was performed to determine the differences in relative growth rates and final fresh weights between the plants illuminated with the laser projector and the fluorescent lamp based on the statistical significance (Sig.).

The weights of the seedlings appeared to be too small to monitor any differences in weight. Therefore, it was chosen to use the plant area in the pictures as a measure for assessing growth. The plant area was segmented from the top-view image using a simple image analysis algorithm.

**RESULTS AND DISCUSSION**

The Showwx™ laser pico-projector was tested in two experiments, where the growth of lettuce seedlings and crops were compared to a fluorescent lamp.

After 12 days of cultivation under the lighting conditions described in Table 2, the lettuce seedlings were able

**Table 2** Initial plant material and lighting conditions for the two experiments using seedlings and crops. Photosynthetic photon flux densities for the crops varied between the top (high value) and the bottom part (lower value) of the plants.

| Plant age (weeks after germination) | Plants per light source (N) | PPFD (μmol m⁻² s⁻¹) | Lighting (h day⁻¹) |
|-----------------------------------|-----------------------------|----------------------|------------------|
| Seedlings                         | 1                           | 6                    | 17               | 24               |
| Crops                             | 4                           | 1                    | 9-15             | 24               |
to develop in size. However, half of the seedlings died during the experiment. Number of surviving plants varied. Only one third of the seedlings illuminated with the fluorescent lamp survived the experiment, while under the laser projector two third of the seedlings survived. The PPFD of only 17 \( \mu \text{mol m}^{-2} \text{s}^{-1} \) was probably too low for these plants. The measurements were taken to accumulate 12 data points throughout the first experiment. The relative growth rate was based on the plant area, which is presented in Fig. 4. The growth rates were not significantly different for the two light sources, but the final fresh weight was higher for the seedlings illuminated with the scanning laser projector.

The lettuce crops have been grown for 10 days as described in Table 2. Both crops survived the experiment and were able to reach a higher weight. The weight differences were large enough to measure each day as shown in Fig. 5. The results are presented in Table 4. The average relative growth rates, based on weight, were not significantly different for the two light sources.

There were more fluctuations in growth rate for the laser projector, which is probably caused by the projector instability. The projector is designed to run for the length of one movie, while in these experiments it was used for continuous lighting. The plants illuminated by the laser projector received thus a lower total number of photons, because the PPFD was not adapted. However, the relative growth rates were similar to the fluorescent light source, indicating that the laser projector might be advantageous.

The plant temperatures were significantly different for the two light sources in both experiments (Tables 3 and 4). The scanning laser projector did not emit any thermal heat, resulting in a lower plant temperature. This will reduce the requirement of cooling inside the plant factory.

A disadvantage of scanning laser projectors is that only the leaves perpendicular to the light direction are illuminated. Curved leaves and the bottom-side were shaded, because the direct laser beams could not reach these parts. Fluorescent light is more diffuse and can penetrate deeper into the crop.

In conclusion, lettuce seedlings and crops (\textit{L. sativa} L. cv. Frillice) were able to grow in size and weight when they were illuminated using a scanning laser projector. There was no significant difference in growth rates compared to the fluorescent light source. For the lettuce seedlings, the final fresh weight was higher for the seedlings illuminated using the laser projector. This was not observed in the cultivation of lettuce crops. The differences were observed under abnormal low lighting conditions, because the laser powers were not large enough to get the desired photon flux. A single Showwx\textsuperscript{TM} laser pico-projector is therefore not suitable for lighting in plant production. However,

| Table 3 | Growth of the lettuce seedlings, where relative average growth rates were based on plant area. |
|---------|------------------------------------------------------------------------------------------------|
| Surviving plants (N) | Measurements (N) | Average plant temperature (°C) | Average growth rate (% day\textsuperscript{-1}) | Final fresh weight (g) |
| Fluorescent | 2 (33%) | 12 | 21.7 ± 0.89 | 7.9 ± 18.1 | 0.047 ± 0.0070 |
| Laser | 4 (67%) | 12 | 19.7 ± 0.89 | 9.9 ± 20.5 | 0.079 ± 0.0071 |
| Sig. | — | — | 0.000 | 0.708 | 0.006 |

| Table 4 | Growth of the lettuce crops, where relative average growth rates were based on weight differences. |
|---------|------------------------------------------------------------------------------------------------|
| Surviving plants (N) | Measurements (N) | Average plant temperature (°C) | Average growth rate (% day\textsuperscript{-1}) | Final fresh weight (g) |
| Fluorescent | 1 (100%) | 7 | 21.4 ± 0.53 | 4.1 ± 2.91 | 29.4 |
| Laser | 1 (100%) | 7 | 19.0 ± 0.87 | 4.3 ± 6.53 | 24.4 |
| Sig. | — | — | 0.000 | 0.946 | — |
higher power scanning laser projectors seems to be a promising to maximize the light efficiency and decreasing production costs in a plant factory.

REFERENCES

Blankenship, R. 2002. Molecular mechanisms of photosynthesis. Photosynthetica 40: 12.

Buckley, E. 2012. Detailed eye-safety analysis of laser-based scanned-beam projection systems. J. Display Technol. 8: 166–173.

Freeman, M., Champion, M., Madhavan, S. 2009. Scanned laser pico-projectors: seeing the big picture (with a small device). Optics Photonics News 20: 28–34.

Nobel, P. S. 2009. Physicochemical and Environmental Plant Physiology. Academic Press, Oxford, pp 582.

Watanabe, H. 2009. Light-controlled plant cultivation system in Japan-development of a vegetable factory using LEDs as a light source for plants. Acta Hortic. 907: 37–44.

Yamazaki, A., Tsuchiya, H., Miyajima, H., Honma, T., Kan, H. 2000. Growth of rice plants under red laser-diode light supplemented with blue light. Acta Hortic. 580: 177–181.