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# Deliverable 4.421
# Definition of optimal steady-state SSL emission spectrum and specifications of a light engine for crop growth

| | |
|---|---|
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# D 4.421

# Definition of optimal steady-state SSL emission spectrum and specifications of a light engine for crop growth

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| **PU** | Public | X |
| **PP** | Restricted to other programme participants (including the European Commission Services) | |
| **RE** | Restricted to a group specified by the Consortium (including the European Commission Services) | |
| **CO** | Confidential, only for members of the Consortium (including the European Commission Services) | |

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# CONTENTS

# List of abbreviations

| | |
|---|---|
| FIR | Far infra-red (3000 – 1000000 nm) |
| FR | Far red (700 – 800 nm) |
| HPS | High pressure sodium |
| LED | Light emitting diode |
| NIR | Near infra-red (700 – 3000 nm) |
| PAR | Photosynthetically active radiation (400 – 700 nm) |
| Pr | Inactive form of phytochrome |
| Pfr | Active form of phytochrome |
| PSS | Phytochrome stationary state |
| UV | Ultraviolet (0 - 400 nm) |

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# SECTION 1 – Introduction

Light behaves as a series of waves, and plants are sensitive to wavelengths occurring between 400 and 700 nm, the area of visible light also called PAR [1], (photosynthetically active radiation). However, the light energy necessary for the energy requirements of the photosynthetic process is contained in small particles called photons or quanta. Because photosynthesis is not related to the energy content of light, but to the number of photons, light related to photosynthesis is expressed in moles of photons per unit area per second (µmol $m^{-2}$ $s^{-1}$). The energy content differs per wavelength, for example the energy of a 400-nm photon (blue) is 1.75 times higher than that of a 700-nm photon (red), but for the process of photosynthesis both photons are equivalent. Thus, solar radiation expressed in W $m^{-2}$ (energy), overestimates the effect of blue light and underestimates the effect of red light in terms of photons.

Plants use light for the process of photosynthesis (assimilation light or supplemental light) as well as for photomorphogenesis, plant development and cellular metabolism (light quality or steering light). Both light requirements are necessary in greenhouse horticulture and are described separately here below.

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# SECTION 2 – Light in horticulture

The horticultural area in the Netherlands is approximately 10 000 ha. [2], of which an increasing area uses artificial lighting. At present artificial lighting is used on about 3100 ha., one third of the total horticultural area. Artificial lighting is primarily used for cut flowers, mainly rose and chrysanthemum (2400 ha.), as well as for vegetables like tomato, bell pepper and cucumber (700 ha.).

Light in horticulture is essential for year-round production. In the winter months however, there is insufficient sunlight in greenhouses for horticultural crops (Figure 1), with light sums of less than 5 moles $m^{-2}$ $day^{-1}$. Crops often require at least 8-10 moles $m^{-2}$ $day^{-1}$ so that artificial lighting often supplements the amount of sunlight. When artificial lighting is not present, the production of flowers is drastically reduced and production of vegetable fruits like tomato is absent in the winter.

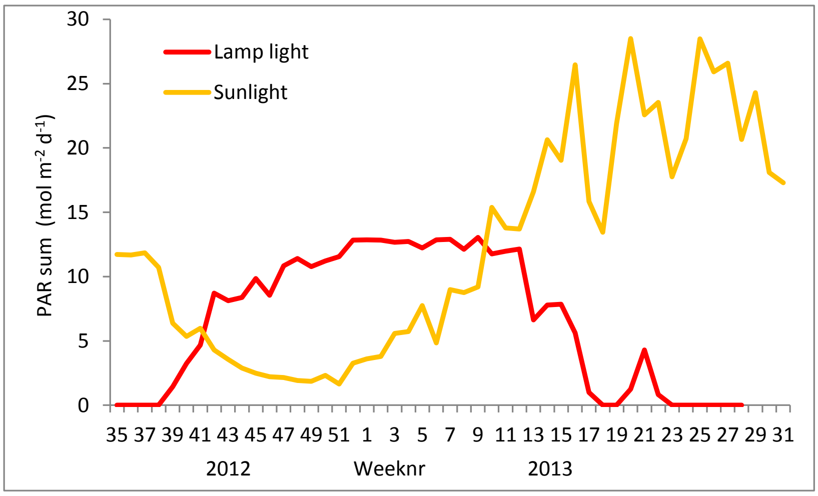


**Figure 1**. The amount of natural light (sun light) and artificial light (lamp light) (light sum, mol $m^{-2}$ $d^{-1}$) in a greenhouse in the Netherlands (2013-2014).

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# SECTION 3 – Assimilation light

Plants require light for growth. Sun light when possible and often (in northern temperate zones) artificial light when necessary. In general, horticultural crops require as many photons as are available, because more light results in more growth. The rule of thumb is that 1% more light results in 1% more production. As the light intensity increases in the first 200-400 μmol/m$^2$/s, photosynthesis is linearly related to the light intensity; thereafter photosynthesis depends on the level of $CO_2$ and yet later on, on other limiting factors. There is a limit however, to the light intensity a plant can utilize and the limit is different for each species and has to do with its photosynthetic capacity. Some crops like rose or tomato have a large photosynthetic capacity and are able to utilize high light intensities or a long light duration. Others, called shade tolerant crops, require less light and at higher light intensities, photosynthesis is inhibited, excess light energy must be dissipated and the photosynthetic apparatus may become damaged.

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# SECTION 4 – Assimilation lighting

Horticultural crops require relatively high levels of assimilation light. They require an 'average sunlight' spectrum of PAR light (photosynthetically active radiation) so that the crop growth and development takes place as the grower desires. When more light is necessary than sunlight can provide for year-round production, assimilation lamps are often used. The most common type of assimilation lamps in horticulture are HPS (high pressure sodium) lamps, with the yellow/orange wavelengths of light dominating the PAR spectrum.

There are various HPS lamps available, varying in light capacity (for the different light requirements per crop), size (relevant for the interception of sunlight), and type of reflector (important for a homogeneous light distribution). The specifications of the most common HPS lamps in the Netherlands are summarized on Table 1. When used for comparison within HI-LED project, 1000W HPS lamps will be considered.

**Table 1**. Specifications of assimilation lighting lamps used in Dutch horticulture.[3]

| **HSE600 Lamp** | | | | | | |
|---|---|---|---|---|---|---|
| Type | Electrical consumption | Voltage/ frequency | Power consumption | Tolerance lamp (VSA) | Power factor (cos ø) | Weight* |
| 600W | 400V | 1.61 A | 635W | 9% | 0.98 | 4.3 kg |
| 1000W | 400V | 2.61 A | 1032W | 9% | 0.98 | 4.7 kg |
| **HS2000 Lamp** | | | | | | |
| 400W | 2.3 A | 230V/50Hz | 445W | ±5% | >0.85 i | 9 kg |
| 600W | 3.3 A | 230V/50Hz | 645W | ±5% | >0.85 i | 11 kg |
| 600W | 1.85 A | 400V/50Hz | 645W | ±5% | >0.9 i | 11 kg |
| **HSX Lamp** | | | | | | |
| 600W | 1.85 A | 400V/50Hz | 645W | ±5% | >0.9 i | 8 kg |
| **HSX II Lamp** | | | | | | |
| 1000W | 2.61 A | 50/60Hz | 1032W | ±5% | >0.95 i | 3.6 kg |
| **HSE Daylight Lamp** | | | | | | |
| 350W | 1.5 A | 230V/ 50-60Hz | | | | 6.3 kg |

The most commonly grown horticultural crops under glass have differing (ranges of) light requirements, which are accommodated by these lamps. These are briefly given in Table 2.

Assimilation lighting is usually applied as top light, with lamps or light modules located 1-1.5 m above the canopy. Before positioning the lamps in the greenhouse, a light plan is made in which lamps are placed such that they provide a homogeneous blanket of light on the crop, at the top of the canopy. In this way, all parts of the crop in a horizontal plane receive the same amount of light.

There is an alternative manner of providing some crops like high-wire vegetables, gerbera and strawberry with assimilation light currently in use. In order to bring more light deeper into the crop and simultaneously reduce the interception of sunlight, modules with LEDs (light emitting diodes) are placed in the crop, about the middle of the crop to bring more light to the often shadowed lower leaf canopy. The term applied to this lighting system is 'interlighting'. When combined with HPS top light, it is called a 'hybrid lighting system'.

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**Table 2**. Commonly grown horticultural crops, light requirements and the types of lamps used to grow them (indicated with 'X').

| Crop | Light range required (µmole/m2/s) | Lamp type [3] | | | | |
|---|---|---|---|---|---|---|
| | | HSE600 | HS2000 | HSX | HSX ii | HSE Daylight |
| **Vegetables** | | | | | | |
| Tomato | 170-200 | X | X | X | X | |
| Pepper | 70-130 | X | X | X | X | |
| Cucumber | 100-200 | X | X | X | X | |
| **Cut Flowers** | | | | | | |
| Chrysanthemum | 105-130 | X | X | X | X | |
| Rose | 170-200 | X | X | X | X | |
| Lily | 80-100 | X | X | X | X | |
| Lisianthus | 170-200 | X | X | X | X | |
| Alstroemeria | 60-105 | X | X | X | X | |
| Anthurium | 80-105 | X | X | X | X | |
| Freesia | 70-105 | X | X | X | X | |
| Gerbera | 80-105 | X | X | X | X | |
| Tulip | 25-40* | X | X | X | X | |
| **Potted plants** | | | | | | |
| Phalaenopsis | 80-130 | X | X | X | X | |
| Dendrobium | 130-160 | X | X | X | X | |
| Bromeliad | 40-60 | X | X | X | X | |
| Anthurium | 60-80 | X | X | X | X | |
| Kalanchoe | 60-105 | X | X | X | X | |
| Pot chrysanthemum | 40-60 | X | X | X | X | |
| Pot rose | 40-60 | X | X | X | X | |
| Geranium | 40-60 | X | X | X | X | |
| **Propagation** | | | | | | |
| Cuttings for flowers | 60-130 | X | X | X | | X |
| Vegetable seedlings | 60-80 | X | X | X | | X |

*in combination with extra blue light

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# SECTION 5 – Steering light

The term 'steering light' refers to light quality (colour) in combination with intensity, light duration and time of application. PAR light is composed of different colours, or wavelengths. What we see is not what a plant perceives and responds to. While our sight especially sees green, yellow and orange colours, plants respond more to blue and red. Thus, different parts of the visible light spectrum, and some wavelengths just outside of PAR (see Figure 2), are readily perceived by plants and trigger plant responses, resulting in changes in plant morphology and physiology. This light-driven process is called photomorphogenesis. Morphogenesis determines plant architecture, flower colour and complex processes like flowering. In general, a light spectrum similar to that of sunlight is thought to guarantee a normal plant development.

When expressed as a percentage of all photons between 400 and 800 nm, sunlight is composed of 21% blue light (400-500 nm), 26% green (500-600 nm), 27% red (600-700 nm) and 26% far red radiation (700-800 nm). Plant requirements for blue light vary per species, and some species grow well in light with virtually no blue light, while others require more blue light. The effect of blue light depends on the red:far red ratio.

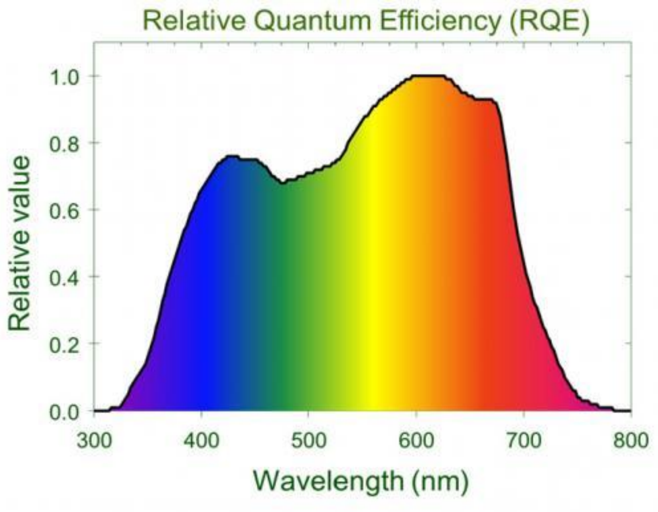


**Figure 2**. The relative quantum efficiency or the relative sensitivity of different areas of PAR (photosynthetically active radiation). Adapted by Erik Runkle (Michigan State University Extension, Department of Horticulture) from McCree, 1972. (Agric. Meteorology 9:191-216.) [4]

In addition to photosynthetic active pigments, plants also possess special pigments called photoreceptors. Photoreceptors receive signals from the plant's environment, information to which plants can respond, i.e. light intensity, spectral composition, day/night and seasonal rhythms as well as the direction of light. These signals can stimulate or inhibit plant hormones, which in turn influence a large number of plant responses. The balance between different hormones (auxins, gibberellins, cytokinins and ethylene) regulates plant processes like stem elongation, leaf orientation, induction of flowering, distribution of assimilates and ageing.

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The most well-known photoreceptors in plants are phytochrome, cryptochrome and phototropins. Phytochromes are sensitive to the whole light spectrum, from UV to far red, but respond especially to the red and far red wavelengths. Red light is absorbed by the inactive form of phytochrome (Pr) and far red by the active form (Pfr). By changing the amount of red relative to far red light, the phytochrome balance or phytochrome stationary state (PSS) changes. The PSS affects the plant via the hormone balance and regulates many plant processes like flower bud development, elongation, bud break and senescence.

Cryptochromes and phototropins  are sensitive to wavelengths in the UV and blue/green area of the spectrum. The light spectrum influences the plant's biological clock, leaf thickness and elongation via the cryptochrome photoreceptor. For example, blue light inhibits elongation by inhibiting the elongation stimulating hormone gibberellin. Phototropins influence the direction in which plants grow (towards the light) and stomatal opening.

Through these signals, the plant can respond to changes in its environment. An example is that of a plant growing in the shadow of another plant. Because leaves transmit a great deal of far red light, the plant growing in the shadow receives a relatively large amount of far red light and relatively less red and blue light. This signal stimulates the hormone gibberellin and the plant elongates. In addition, because the plant receives less blue light, the elongation is even further stimulated and the plant invests more in its shoot growth. The plant growing in full sunlight receives the opposite signals so that the plant invests more in its roots, auxillary shoots and leaves, resulting in a compacter plant.

**Table 3**. Some general plant responses to different wavelengths of light in the ultraviolet (UV), photosynthetic active radiation (PAR), near infra-red (NIR) and far infra-red (FIR) regions.

| | Radiation | Wavelength (nm) | Some general plant responses |
|---|---|---|---|
| UV | UV C | 0-280 | <300 nm does not reach the earth |
| | UV B | 280-320 | Stimulates secundary metabolites (300-320 nm) |
| | UV A | 320-400 | Hardening |
| PAR | Blue | 400-500 | Stomatal opening |
| | | | Photosynthesis |
| | | | Inhibits elongation |
| | | | Stimulates leaf thickness |
| | Green | 500-600 | Photosynthesis |
| | | | Much reflected |
| | Red | 600-700 | Stimulates chlorophyll synthesis |
| | | | Stimulates auxillary shoots |
| | | | Photosynthesis |
| | | | Inhibits elongation |
| | | | Stimulates germination |
| | | | Induces flowering in LDP |
| | | | Influences photoperiodism |
| NIR | Far red | 700-800 | Inhibits germination |
| | | | Stimulates elongation |
| | | | Inhibits flowering in LDP |
| | Near infrared | 700-3000 | Mostly heat radiation |
| FIR | Far infrared | 3000-100000 | Only heat radiation |

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# SECTION 6 – Lighting systems to influence morphogenesis

Conventional artificial light systems meet some of the requirements for morphogenesis while not always having been specifically designed for that purpose. For example, strawberry plants even now are exposed to incandescent lamps to influence flowering and fruit production. Incandescent lamps yield a relatively large proportion of far red light, and it was this lower red:far red ratio that transformed the active form (Pfr) of phytochrome to the inactive form (Pr), which in turn alters the hormone balance in strawberry to flower and produce strawberries.

High pressure sodium (HPS) lamps developed from the street lamp and under the resulting proportion of yellow/orange, red and far red wavelengths, plants grew very adequately. This has resulted in the extensive use of these lamps in horticulture. It is also quite likely that the not often recognized influence of HPS lamps, i.e. the steering influence of the HPS spectrum, on the morphogenesis of various crops has contributed to its effectiveness in plant growth and production.

In climate rooms without natural sunlight, metal halide lamps are often used in addition to HPS lamps, due to their increased proportion of blue light. Natural sunlight contains ca. 27% blue light and because the blue light component of HPS lamps is ca. 5%, metal halide lamps were used to supplement the blue.

However, during the past decade light emitting diodes (LEDs) have made their introduction into horticulture. Starting with red and blue LEDs, obviously due to their contributions to growth (red) and morphogenesis (blue), LED modules with other wavelengths have made their introduction as well. Although possible to use monochromatic light, LEDs usually emit a band width of 20-50 nm with, for example, a peak at 450 nm for blue light. LED modules are used as top lighting and interlighting in the greenhouse as well closely layered in plant propagation units.

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# SECTION 7 – Specifications of the SSL light engine for crop growth

In WP 4, task 2 (Light spectra for high productivity horticulture), DLO has the task to determine the crop response to constant and variable spectra of SSL modules. The first step is to determine the crop response to a constant spectrum of SSL modules (sub-task 4.2.1). In order to do so, we selected greenhouse compartments in which temperature and light conditions could be fully controlled. Using a background of approximately 20% solar light, plants had to grow under LED light. Based on experience, this implies that the light intensity the LEDs should supply would be 200-250 µmol/m$^2$/s to ensure proper plant growth and functioning.  Furthermore, the light colours to be investigated in this task were selected to be white (reference), green, red, blue, amber and a combination of red and blue. These colours were chosen, first to show their distinct effects on plant processes (see table 3) ( it is the case of red, green and blue), to establish a reference to the orange HPS light characteristics (amber) and comparing the system to the common commercial practice, where LED systems are used that are a combination of red and blue LEDs (red/blue).

The specifications and wavelengths of the LED modules that will be used in WP4, task 2 (Light spectra for high productivity horticulture) are given in Table 4. The intensity required for plant growth is 200-250 µmol m$^{-2}$ s$^{-1}$ on a crop area of 5 m$^2$ (3 tables per experimental greenhouse, total 6 tables, i.e. 6 light colours). The LED modules are fitted with 2 Osram OTI90W drivers [5], (180W LED capacity), 2 LEDs run in parallel with 176 OSLON  SSL LEDs [6], per module.

**Table 4**. Specifications of LEDs for steering light used in the HI LED trials.

| **LED modules**<br>Type | Electrical consumption | Dim level | Output per module (µmol s$^{-1}$) | Modules per table | Output per table (µmol s$^{-1}$) | Mean light intensity (µmol m$^{-2}$ s$^{-1}$) |
|---|---|---|---|---|---|---|
| White mix | 96W | 89%=90W | 123 | 14 | 1722 | 250 |
| Red 660 nm | 96W | 53%=54 W | 123 | 14 | 1722 | 250 |
| Blue 460 nm | 96W | 75%=77W | 123 | 14 | 1722 | 250 |
| Green 510 nm | 96W | 81%=83W | 62 | 28 | 1722 | 250 |
| Yellow/Amber 580/610 nm | 96W | 100%=96W | 105 | 14 | 1470 | 210 |
| Red/blue (92/8) | 96W | 58%=60W | 123 | 14 | 1722 | 250 |

The costs of the modules averages at €231 each. This relatively high cost price is due to the large number of LEDs necessary in each luminaire in order to realize the required light intensities.

Given the specifications provided in table 4, and the fact that the light intensities of all light colours should be identical in order to compare plant growth and development, light intensities in all treatments was set at 210 µmol m$^{-2}$ s$^{-1}$.

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# SECTION 8 – Current and future activities

The status of Task 4.2 is in November 2014 that the LEDs of the different light colours have been supplied by Hortilux, and are installed in the greenhouses. The first trials have been performed, with marked effects on plant growth and morphology. These results will be described in Deliverable 4.422 before Month 24. In the pictures below, the set-up of the LED modules can be seen.

**Figure 3**. Young tomato plants growing under (from top-left to bottom-right) red+blue LEDs, red LEDs, green LEDs, white LEDs, amber LEDs and blue LEDs

Based on the results of sub-task 4.2.1 (crop response to constant spectrum), we will identify different strategies of variable spectra for plant growth. These will be tested in sub-task 4.2.2. The performance of the plants will be tested by using chlorophyll fluorescence techniques (sub-task 4.2.3) in the coming months.

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