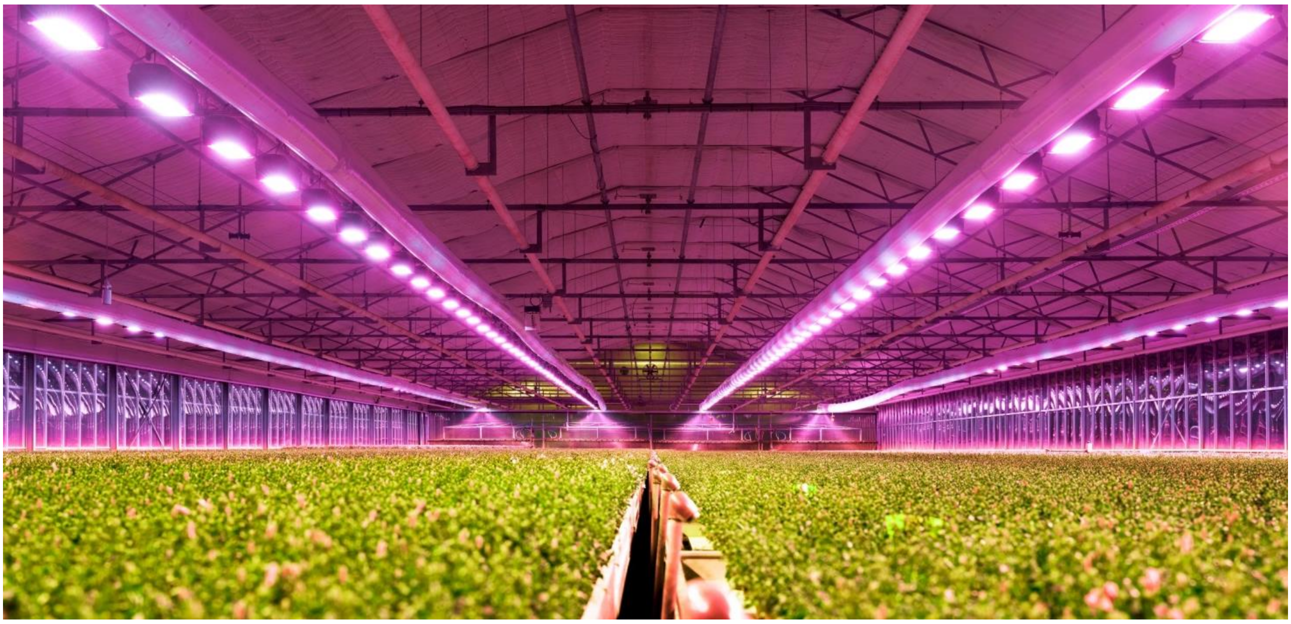

EUDP- Demonstration and integration of energy saving LED luminaires for greenhouses

2. Project details

Project title	Demonstration and integration of energy saving LED luminaires for greenhouses
Project identification (program abbrev. and file)	64010-0097 (EUDP 2010-I)
Name of the program which has funded the project	EUDP
Project managing company/institution (name and address)	Fionia Lighting A/S Industrivej 8 5471 Søndersø
Project partners	Fionia Lighting A/S Gartneriet PKM A/S Senmatic A/S Syddansk Universitet, Institut for Signaler, Sensorer og Elektroteknik
CVR (central business register)	31781795
Date for submission	13-03-2015

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Appendix

3. Short description of project objective and results

English:

The objective of this project was to construct and demonstrate an LED luminaire for greenhouse production. The demonstrations was made both in full scale and in research environment with focus on energy saving and plant responses.

The project resulted in a full 1.500 m2 greenhouse production unit at the greenhouse of PKM equipped with 224 luminaires named FL300. All luminaires where controllable with the LCC4 unit so the system could be controlled both with spectrum and intensity change. The luminaires have proven themselves successful both in terms of stability, light maintenance and plant quality.

The plant results from all three sites tested during this EUDP project showed two main responses aside from saving between 40-50 % of energy. The first respond was the ability to control the plants with the intensity of blue light to reduce the use of chemicals is a payable benefit. The second the ability to control the intensity of the luminaires during the day cycle had a good impact on the stability of the production.

Danish:

Formålet med projektet var at konstruere og teste et LED-armatur til produktion i gartnerier. Testene blev lavet både i fuld størrelse og i et forsknings miljø med fokus på energibesparelser og plante reaktion.

Resultatet af projektet var en installation med 224 FL300 armaturer på et 1500 m2 produktions areal i gartneriet PKM. Armaturerne blev styret med en LCC4, hvor både intensiteten og spektra kunne varieres. Armaturerne viste både en god stabilitet, lys stabilitet og plante kvalitet.

Planteresultatet fra alle tre test metoder i dette EUDP projekt viste to vigtige resultater ud over en energibesparelse på 40-50 %. Det ene resultat viste evnen til at styre planter med mængden af blåt lys til at reducere brugen af kemikalier hvilket er indbringende fordel. Det andet var evnen til at kontrollere intensiteten af armaturerne i løbet af dagen havde en stor indflydelse på at produktionen blev stabil.

4. Executive Summary

With an annual electricity consumption of approx. 200 GWh for supplemental lighting alone and a carbon footprint in the region of 470,000 tons per year, the nursery garden sector is one of Denmark's most energy demanding industries – an industry under pressure from rising energy costs and increased competition from the rest of Europe, particularly Holland, leading to lower sales prices and higher demands on product quality.

This project application and the technology shift from traditional supplemental lighting to energy effective LED fixtures will result in a 50 % saving on electricity costs, benefitting both the environment and the individual greenhouse grower – in the case of PKM nursery garden this saving corresponds to 7 MDKK per annum. With this application, we create a showcase to demonstrate and facilitate the integration of this novel technology into the horticultural industry

The basis for this project is fundamental research conducted at the University of Southern Denmark (SDU) and an ongoing EUDP project. The results are still under analysis, but demonstrate the technology's ability to reduce the electricity bill with the following added benefits: reduction of chemical usage, the ability to manipulate plant appearance, and regulation of light intensity and spectrum to compensate for variations in the available natural light and fluctuating electrical prices.

The results of the project can for easy overview be divided into the following main results:

- A working demonstrated LED fixture for commercial application
- A complex control system for large production greenhouses
- A simple control system for test facilities
- An extensive research part with a PhD thesis as product

The project and the fixture are still in its early phase but we already see a huge interest in the fixture and our ability to control the fixture. Senmatic and Fionia Lighting has joined forces in selling these systems to the world, and the combination of an advanced LED fixture and the ability to control it as easy as everything else in the greenhouse seems to make a difference for the growers. These factors resulted in closing two large orders late 2014 for Holland, which was the original plan. These orders are directly a result from EUDP. Growers are traveling from Holland to our demonstration site in Denmark seeing the fixtures and the control at work, buying a small installation and then after a test run purchasing lamps for whole greenhouses.

5. Project objectives

The objective of the project was controlled via eight work packages, with the following three milestones:

M1: Result of modulation analysis

M2: A finished updated prototype fixture

M3: A fully integrate able LED fixture

All three milestones were archived and in general the combination of the work packages and the two first milestones is key element in archiving milestone 3. The overall project plan and time plan was followed all though two main work packages were altered a delayed.

It proved more difficult than expected to hire a good quality PhD to handle the research part of the project, and the University part of the project was therefore delayed. This situation delayed the whole project unfortunately, since the research program is determined to last three years. This had no impact on the milestone three accomplishment, since we planned the activities so that the results needed for the fixtures was in the first period of the program, and the teaching and article/thesis construction was in the last part.

The approval of the fixture was never meant to be fully completed during the project, but it still proved more expensive and more difficult than expected. Work package seven was completed, although there was a large activity outside this project to cover for this large task.

In general the project and the objectives were met in a satisfactory manner.

6. Project results and dissemination of results

The results of the project can for easy overview be divided into the following main results:

- A working demonstrated LED fixture for commercial application
- A complex control system for large production greenhouses
- A simple control system for test facilities
- An extensive research part with a PhD thesis as product

These main results will be discussed in more detail in the following pages, and a detailed list of publications is shown in Appendix 3.

6.1 Future projections

The project and the fixture are still in its early phase but we already see a huge interest in the fixture and our ability to control the fixture. Senmatic and Fionia Lighting has joined forces in selling these systems to the world, and the combination of an advanced LED fixture and the ability to control it as easy as everything else in the greenhouse seems to make a difference for the growers. These factors resulted in closing two large orders late 2014 for Holland, which was the original plan: To penetrate new markets with this new technology.

We launched the first fixtures in 2012 on the commercial platform, and we sold some without profit in 2012/2013, but the main driver has been Q4 2014. The main reason for this is market adaption, a process where the growers needs to be sure of the technology.

The second part of that equation was that we were able to make a strong connection together with Osram (diode supplier) to ensure a stable low cost supply of diodes for our fixtures. This enables us to sell them to the growers, so that the growers have a payback time of 3-4 years.

With these new impacts we see the business of Fionia Lighting growing with an additional two educated people in the next 12-24 months.

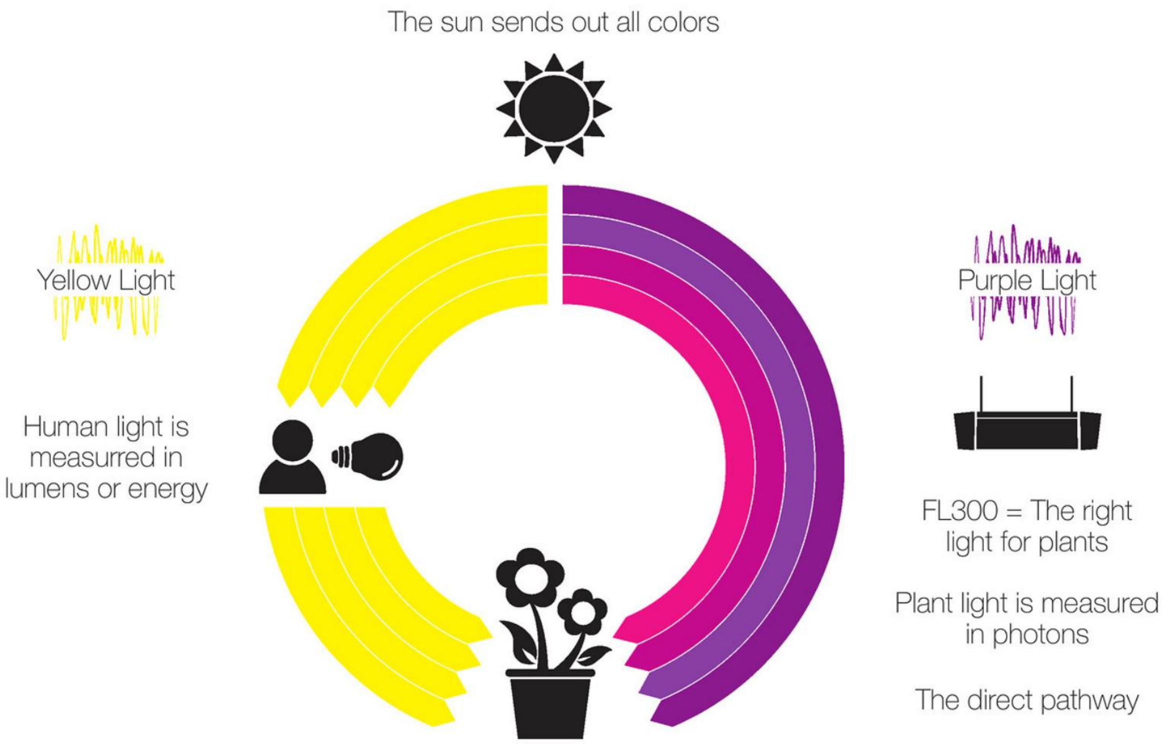
We see the business of Senmatic increase with 4-6 people with no education and two educated people in the next 12-24 months. Senmatic expect sales of FL300 to increase with a twofold from 2014 to 2015 and again from 2015 to 2016. They expect an increase in additional hardware following the fixtures of about 10%.

PKM will continue to utilize the energy savings in this new diode technology, and has since the project ended purchased additional two led facilities to ensure more savings and increase in plant quality.

The University of Southern Denmark has established a new platform in lights, and is sending our applications to further strengthen the application of LEDs.

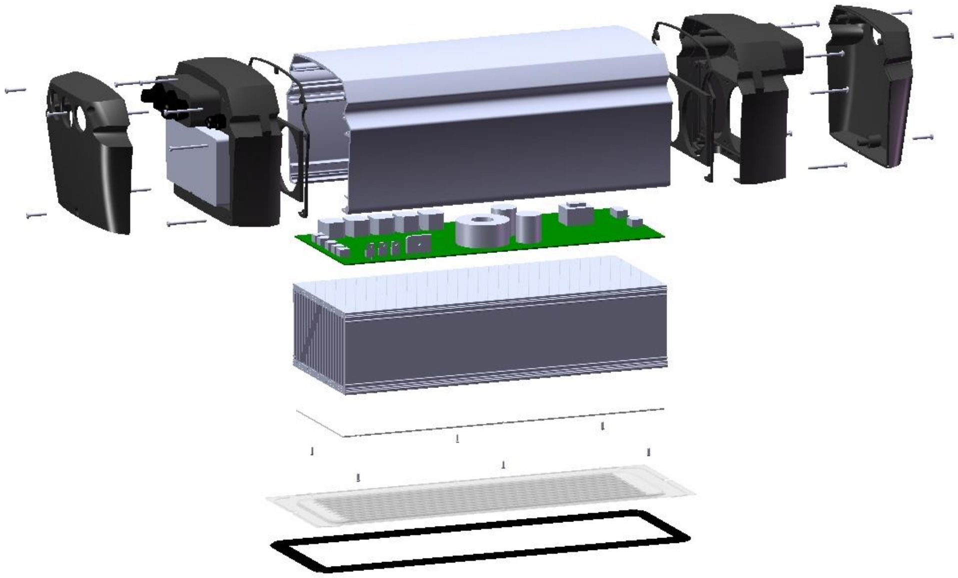
6.2 *FL300 Fixture*

The established technology for supplemental lighting in the nursery garden sector is the high pressure sodium (HPS) lamp and to a much lesser degree fluorescent and filament lamps. The HPS lamp has been the most widely chosen technology for decades because it is the cheapest way to produce high intensity light. Despite this, only about 40% of the electrical energy input to a HPS lamp is emitted as visible light, with the rest being converted to infrared emission and heat.



It is well-documented in the literature, that physiological studies of plant growth have demonstrated that photosynthesis is most efficient for light in the blue (400 – 500 nm) and red (600 – 700 nm) regions of the visible spectrum due to high absorption in chlorophyll at these wavelengths. Therefore, it is commonly acknowledged that traditional HPS lamps, which predominantly emit orange light, can be replaced with LEDs emitting light specifically targeting the most efficient photosynthetic wavelengths, resulting in significant energy savings. However, it is only recently, through the arrival of high brightness LEDs and their implementation in the automotive and retail markets, that LED technology has reached a level of maturity and cost-effectiveness, which justifies its use in large-area illumination applications such as supplemental lighting in the horticulture industry.

The designed FL300 is shown here in an exploited view with the main components shown:



There are several complex elements in creating a LED fixture and three of them are:

Cutting-edge LED technology

The use of LEDs developed in cooperation with manufacturers to obtain the most efficient devices available for producing light at optimal photo synthetically active wavelengths. LED technology is under constant development and the LEDs available for this project are projected to produce 30% more light per watt than those used in the designed prototype. This will allow us to provide higher light intensities without compromising our 50 % saving in electricity consumption. The diodes used are made together with Osram Germany.

Efficient optics

The design of the optical system must minimize losses within the fixture as well as maximize targeting efficiency of the desired illumination area. Whilst the light distribution of the prototype optics is satisfactory, a further optimization is required to reduce optical losses and prepare the fixture for mass production. The optical solution shown has two main functions a front plate shielding the LED’s and an optical function.

Surplus heat recovery

The function of the surplus heat recovery system is twofold: it must collect and transport the heat energy generated in the fixture for redistribution where needed as efficiently as possible and just as importantly, it must provide adequate cooling of the LEDs to prolong component lifetime and ensure optimal light output efficiency. The implemented solution for is a patented cooling solution developed by SAPA, Sweden, which enables sufficient cooling of the LEDs and enable easy installation compared to traditional water cooled LED systems.

In the EUDP project the system is demonstrated and tested in three places: The nursery of PKM, the greenhouse of SOGO TEAM, and the research station Aarslev under The University of Southern Denmark.

Pictures of the installation are shown below, and results of these installations are shown later on.

The Fixtures have been commercial available since 2012 for customers, but our first large installations is not sold before late 2014. Here is a section of these installations:

6.3 *Light Control*

Senmatic's part in the EUDP project can be divided into 3 main tasks:

- Integration between the LED fixtures and the Senmatic climate computer "LCC4"
- LED control in the growers office software (Superlink 5), so it is possible to see the historical data for the LED fixtures
- A software solution (Fionia Lighting Interface) for potential customers that does not own a Senmatic Climate computer

These solutions will give the grower an opportunity to use the potential that the Fionia Lighting LED fixtures have regarding the possibility to control the red/blue ratio and the intensity.

6.3.1 LED integration in the climate computer

To control one department/greenhouse the following units are necessary:

1. One Climate Computer called LCC4
2. One I/O (input/output) box called an expansion box

With this system it is possible to control the climate inside the greenhouse, and with the integration of the LED fixtures in the software, the grower can use all the features in the LED fixtures when they are connected to the exp. box.

The LED fixtures together with the new software that is integrated in the LCC4 make the system unique.

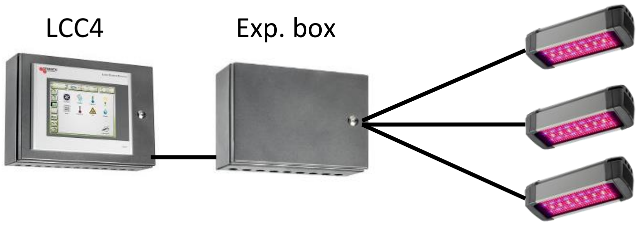


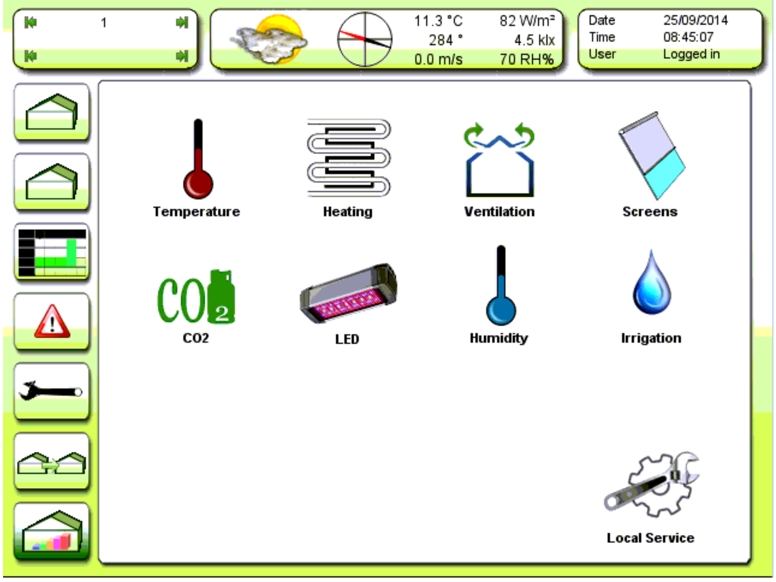
Figure 1: LCC4 and LED installation

The software gives the grower the following ways to control the LED fixtures:

Standard Management:	All fixtures in a group will have the same value.
Light level off:	If the light level by the crops exceeds a value chosen by the grower, the light will be turned off until the light level goes under this value again.
Time Management:	Time controlled LED solution. A grower wants to give his plants 2 hours of only blue light and the rest of the time a standard growth spectrum. It is possible to dived one group into 5 time zones.
Light intensity Management:	A grower wants to keep a stable 250 µmol/m^2/s on his crop. The intensity of the lamps is then dynamically controlled adjusted to the natural sunlight.

Light sum Management:	A grower has a culture that maximum can absorb 9 moles of light pr. day. When that threshold is reached he still wants light due to his long day plants, and the LCC4 turns the level down to e.g. 20 % intensity. It is also possible to turn off the light when the threshold is reached.

When the exp. is used for controlling LED fixtures the department main page shows an LED icon (Figure 2).



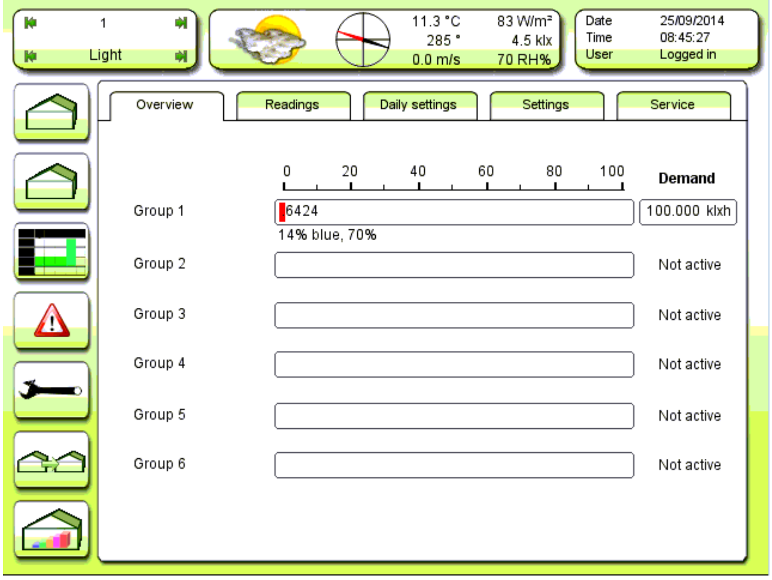
1

11.3 °C
284 °
0.0 m/s
82 W/m²
4.5 klx
70 RH%

Date 25/09/2014
Time 08:45:07
User Logged in

Figure 2: LCC4 department main page

When the grower push the LED icon Figure 3 will appear.



1
Light

11.3 °C
285 °
0.0 m/s
83 W/m²
4.5 klx
70 RH%

Date 25/09/2014
Time 08:45:27
User Logged in

		Demand
Group 1	6424 14% blue, 70%	100.000 klxh
Group 2		Not active
Group 3		Not active
Group 4		Not active
Group 5		Not active
Group 6		Not active

Figure 3: LCC4 overview

As seen on Figure 3 there can be 6 groups of LED fixtures in one department. During the installation each

LED is told which group it belongs to. Only group 1 is active on Figure 3, and the LED fixtures belonging to group 1 is running with the program 14% blue, 70%.

If the grower has 24 LED fixtures it is possible to divide them into 6 groups like shown in Figure 4. And it will be possible to control each group separately.

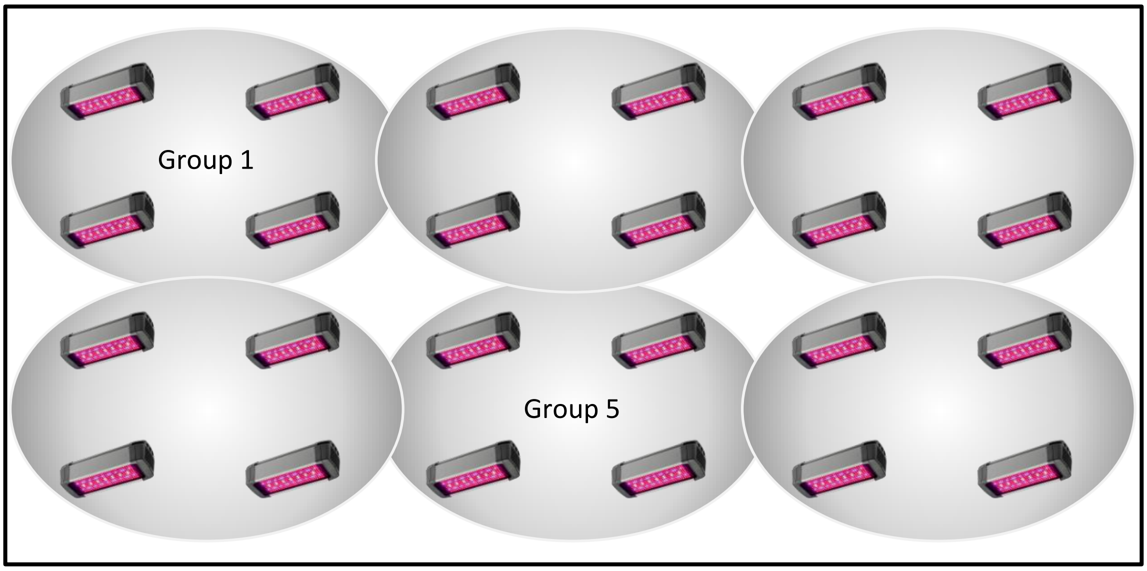
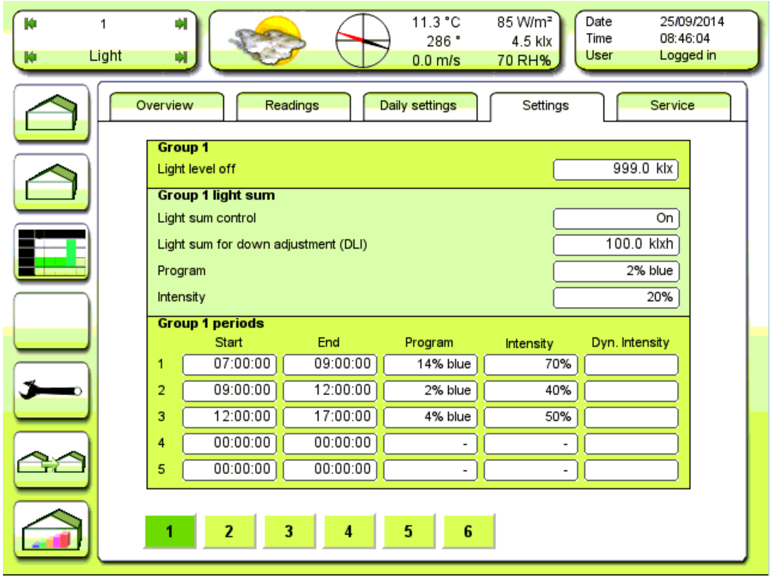


Figure 4: 6 groups

A standard LED expansion can control maximum 2x247 LED fixtures and the max length of each communication line is equal to 1200m. If there are more LED fixtures in one department it is possible to buy an extra module to the expansion, for each extra module it is possible to connect 247 LED fixtures more.

If the tab "Settings" is pushed the grower can control the LED fixtures and decide when they should be on or off and what program the LED fixtures should use.

This page decides which of the features described above (Standard management, Light level off etc.), the installation should use. This is shown in Figure 5.



11.3 °C 85 W/m²
286 ° 4.5 klx
0.0 m/s 70 RH%

Date 25/09/2014
Time 08:46:04
User Logged in

Group 1

Light level off: 999.0 klx

Group 1 light sum

Light sum control: On

Light sum for down adjustment (DLI): 100.0 klxh

Program: 2% blue

Intensity: 20%

Group 1 periods

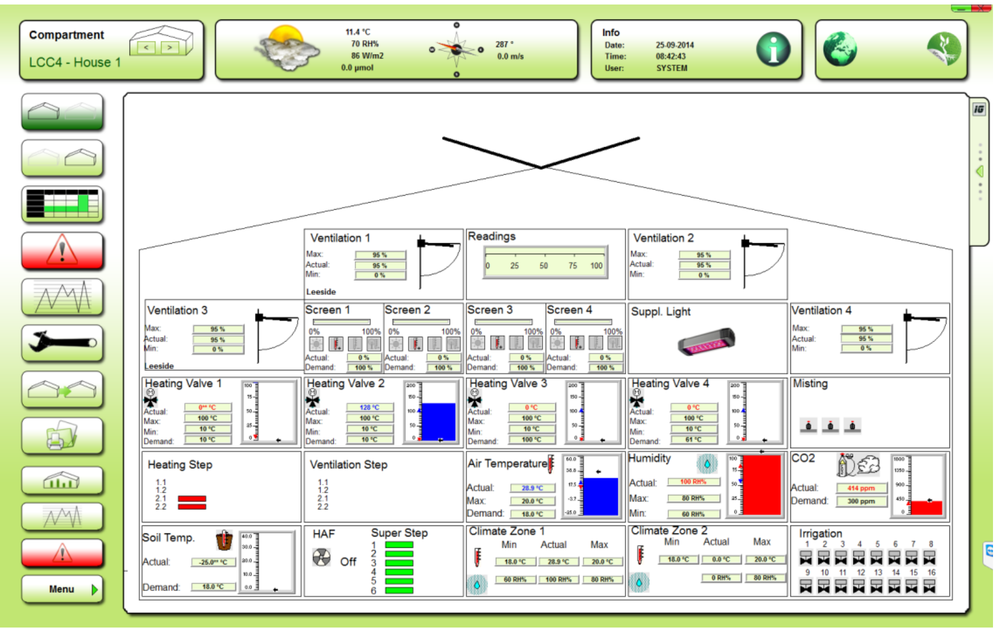
	Start	End	Program	Intensity	Dyn. Intensity
1	07:00:00	09:00:00	14% blue	70%	
2	09:00:00	12:00:00	2% blue	40%	
3	12:00:00	17:00:00	4% blue	50%	
4	00:00:00	00:00:00	-	-	
5	00:00:00	00:00:00	-	-	

Figure 5: LCC4 settings

6.3.2 LED integration in office program (Superlink 5)

Superlink 5 is used to control the climate computer and other computers from Senmatic, from a main office, and to give the grower the possibility to se the historical data of the system.

If there is installed LED fixtures in the department, the department main page shows an LED icon, like shown in Figure 6.



11.4 °C
70 RH%
86 W/m2
0.0 µmol
287 °
0.0 m/s

Date: 25-09-2014
Time: 08:42:43
User: SYSTEM

Ventilation 1 — Max: 95 %, Actual: 95 %, Min: 0 %, Leeside
Ventilation 2 — Max: 95 %, Actual: 95 %, Min: 0 %
Ventilation 3 — Max: 95 %, Actual: 95 %, Min: 0 %, Leeside
Ventilation 4 — Max: 95 %, Actual: 95 %, Min: 0 %
Screen 1 — 0% 100%, Actual: 0 %, Demand: 100 %
Screen 2 — 0% 100%, Actual: 0 %, Demand: 100 %
Screen 3 — 0% 100%, Actual: 0 %, Demand: 100 %
Screen 4 — 0% 100%, Actual: 0 %, Demand: 100 %
Heating Valve 1 — Actual: 0** °C, Max: 100 °C, Min: 10 °C, Demand: 10 °C
Heating Valve 2 — Actual: 128 °C, Max: 100 °C, Min: 10 °C, Demand: 10 °C
Heating Valve 3 — Actual: 0 °C, Max: 100 °C, Min: 10 °C, Demand: 100 °C
Heating Valve 4 — Actual: 0 °C, Max: 100 °C, Min: 10 °C, Demand: 61 °C
Heating Step — 1.1, 1.2, 2.1, 2.2
Ventilation Step — 1.1, 1.2, 2.1, 2.2
Air Temperature — Actual: 28.9 °C, Max: 20.0 °C, Demand: 18.0 °C
Humidity — Actual: 100 RH%, Max: 80 RH%, Min: 60 RH%
CO2 — Actual: 414 ppm, Demand: 300 ppm
Soil Temp. — Actual: -25.0** °C, Demand: 18.0 °C
HAF — Off
Super Step — 1, 2, 3, 4, 5, 6

Climate Zone 1	Min	Actual	Max
	18.0 °C	28.9 °C	20.0 °C
	60 RH%	100 RH%	80 RH%

Climate Zone 2	Min	Actual	Max
	18.0 °C	0.0 °C	20.0 °C
		0 RH%	80 RH%

Figure 6: Superlink 5 department main page

When the grower push the LED icon Figure 7 will appear.

11.4 °C
70 RH%
87 W/m2
0.0 µmol
289 °
0.0 m/s

Date: 25-09-2014
Time: 08:42:54
User: SYSTEM

GROUP 1

	START	END	PROGRAM	INTENSITY	DYN. INTENSITY
1	07:00	09:00	14% blue	70%	0.0 µmol
2	09:00	12:00	2% blue	40%	0.0 µmol
3	12:00	17:00	4% blue	50%	0.0 µmol
4	00:00	00:00	-	-	0.0 µmol
5	00:00	00:00	-	-	0.0 µmol

Light level off	19980.0 µmol
Light sum control	On
Light sum for downadjustment (DLI)	7.2 mol
Light sum program	2% blue
Light sum intensity	20%

READINGS

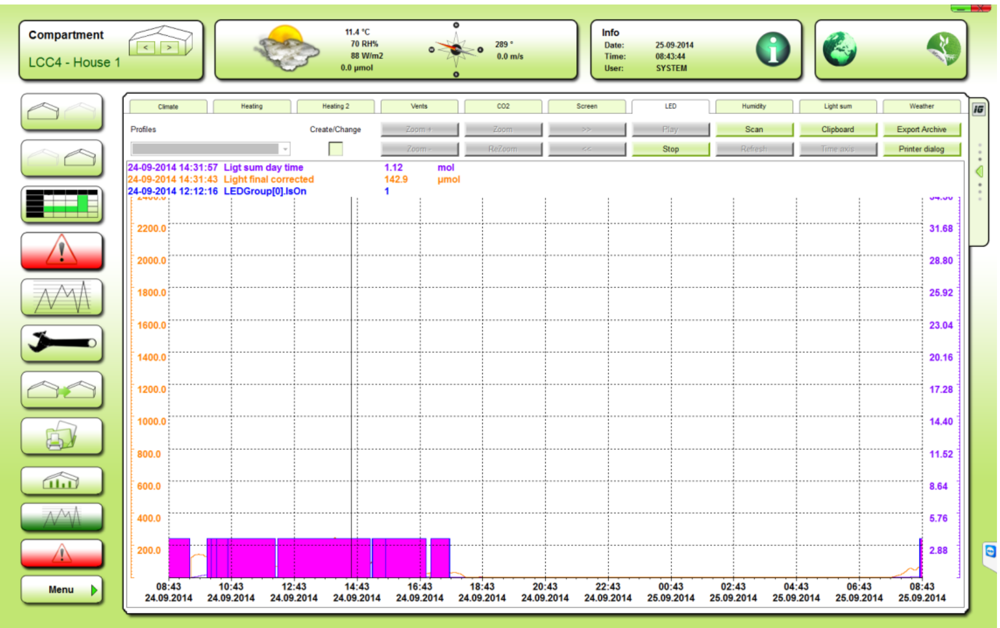
Light active	Yes
Light level	73.6 µmol
Light sum total	0.1 mol
Light active time	5.0 hour

ELECTRICALLY ENERGY

Electrically energy consumed yesterday	0.0 kWh
Electrically energy consumed today	0.0 kWh
Electrically energy consumed total	0.0 kWh
Reset electrically energy consumption total	Reset
Electrically energy counter pulse value	1.000 kWh

Figure 7: Superlink 5 settings

This page is equal to the “setting” tab in the LCC4. So from the Superlink 5 it is possible to control the LED fixtures in the same way as in the LCC4. On Figure 8 historical data from the LED fixtures can be seen.



Compartment
LCC4 - House 1

11.4 °C
70 RH%
88 W/m2
0.0 µmol
289 °
0.0 m/s

Info
Date: 25-09-2014
Time: 08:43:44
User: SYSTEM

24-09-2014 14:31:57 Ligt sum day time 1.12 mol
24-09-2014 14:31:43 Light final corrected 142.9 µmol
24-09-2014 12:12:16 LEDGroup[0].IsOn 1

Figure 8: Superlink 5 Graph

6.3.3 Fionia Lighting Interface

Fionia Lighting Interface Software is a PC program for changing the program in the Fionia Lighting Lamp.

Together with the software there is an interface box.

This box is connected to the USB port at the PC and the communication wires from the lamp is connected to a connector inside the box.

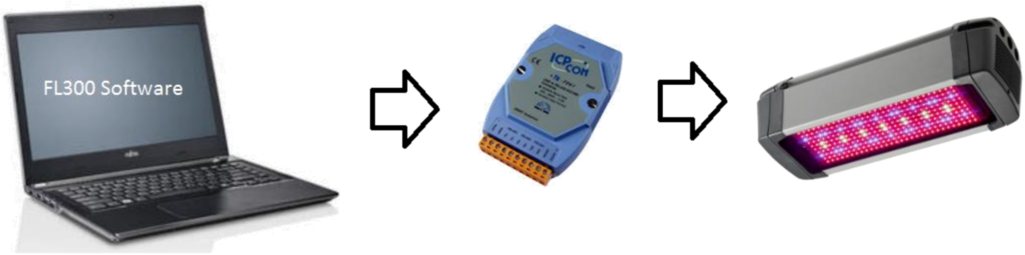
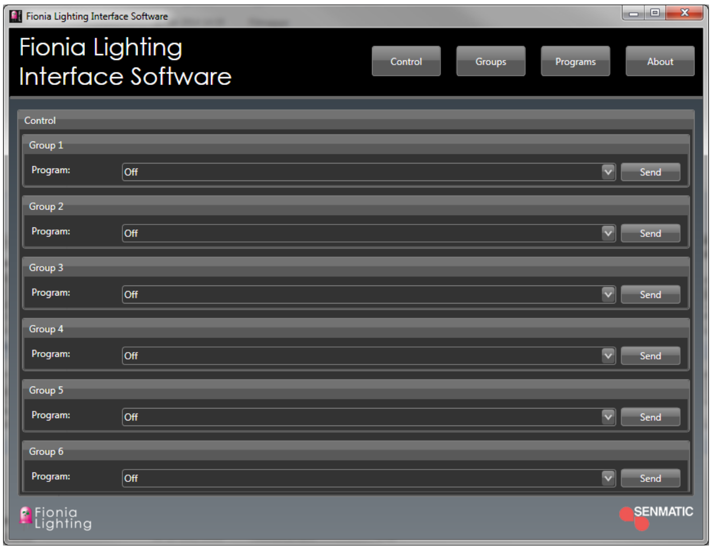


Figure 9: Fionia Lighting Interface

- The software is made for Windows
- The number of LED fixtures is max 49
- It is possible to divide the LED fixtures into Groups
- It is possible to control the 4 channels and the fan
- Possibility to give the lamps different programs 20 % intensity, 4 % blue
- Only connection between the program and the LED fixtures is RS 485. So no sensor input and no outputs

When the program is started it looks like Figure 10.



Control

Group 1
Program: Off

Group 2
Program: Off

Group 3
Program: Off

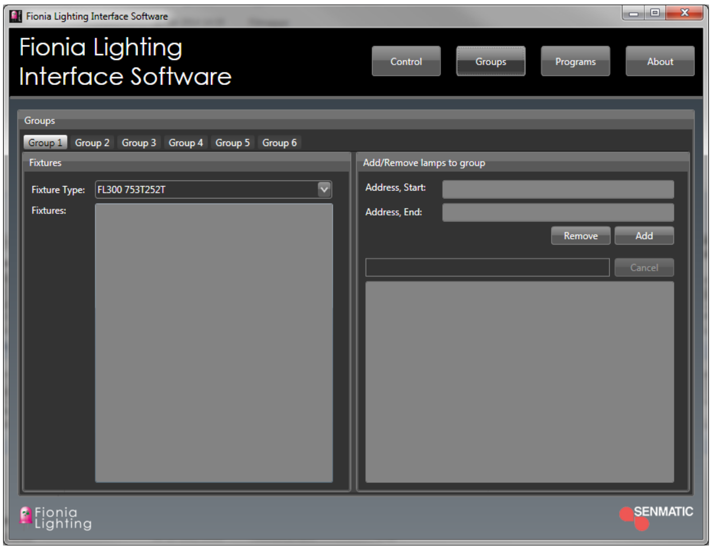
Group 4
Program: Off

Group 5
Program: Off

Group 6
Program: Off

Figure 10: Control page

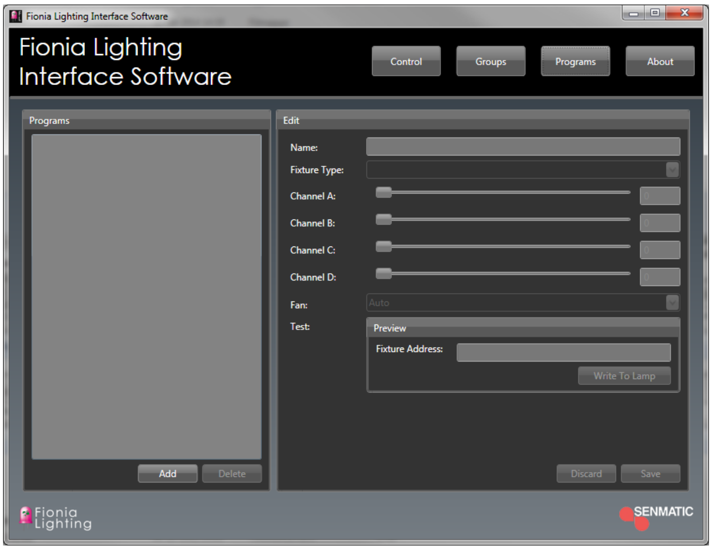
This is where the grower can change the program for all lamps that is in the groups. When the grower push the “Group” box Figure 11 will appear.



Fixture Type: FL300 753T252T

Figure 11: Group page

The group page is where the lamp is told which group they belong to. When the grower push the “Program” box Figure 12 will appear.



Fan: Auto

Figure 12: Program page

The program page is where it is possible to make a new program, it is possible to change the red/blue ratio and the intensity.

6.3.4 Conclusion

With the 3 programs made by Senmatic in corporation with Fionia Lighting in the EUDP project, we have developed a unique integration between the climate control in the greenhouse and the LED fixtures.

6.4 New cultivation methods

LED (light emitting diodes) light spectrum differs from HPS (High pressure sodium lamps). Fionia FL300 LED fixtures for greenhouse production emits light in the blue and red waveband and are optimised to emit light in the same wavelength as chlorophyll absorbs light. Light quality influences growth and development to a certain degree and a change in spectral distribution might lead to a change in growth habit of the plant.

6.4.1 Experiments

In the project two experiments were conducted, each on a number of batches of *Campanula portenschlagiana*.

The first experiment was conducted from 3th January to 10th of April 2012 and the second experiment was conducted from 1st November 2013 to 7th February 2014. In both experiments *Campanula portenschlagiana* was produces in a greenhouse equipped with LED fixtures (Fionia Lighting FL300) and growth and development was compared with plant grown under HPS.

The artificial lighting systems (LED and HPS) provided 130 µmol m^{-2} s^{-1} measured at plant level.

The plants were propagated under HPS and transferred to LED when the plants were spaced the first time.

6.4.1.1 Experiment 1

Fresh and dry weight was measured several times for each batch from spacing to marketable stage. The increase in fresh weight is very similar in both light treatments (Figure 1). There is no seasonal difference increase in fresh weight between LED and HPS (Figure 1 and Figure 2).

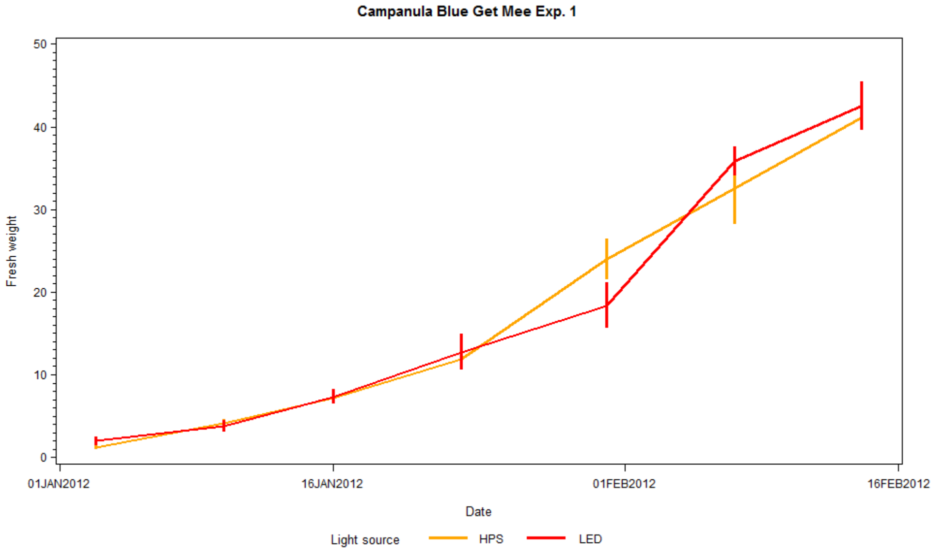


Figure 1: Trajectory of fresh weight [g] of Campanula portenschlagiana grown under LED and HPS (batch 1)

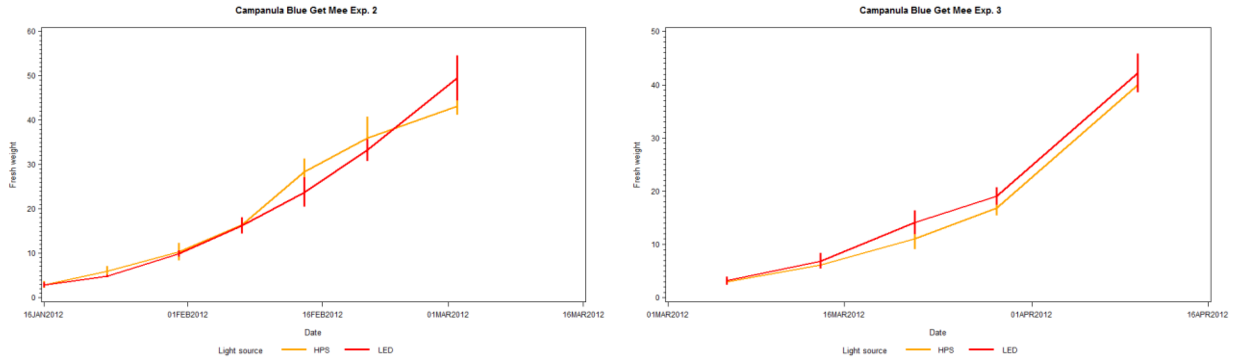


Figure 2: Trajectory of fresh weight [g] of Campanula portenschlagiana grown under LED and HPS (batch 1 and 2)

The increase in dry weight is very similar to fresh weight and is identical for both lamp types.

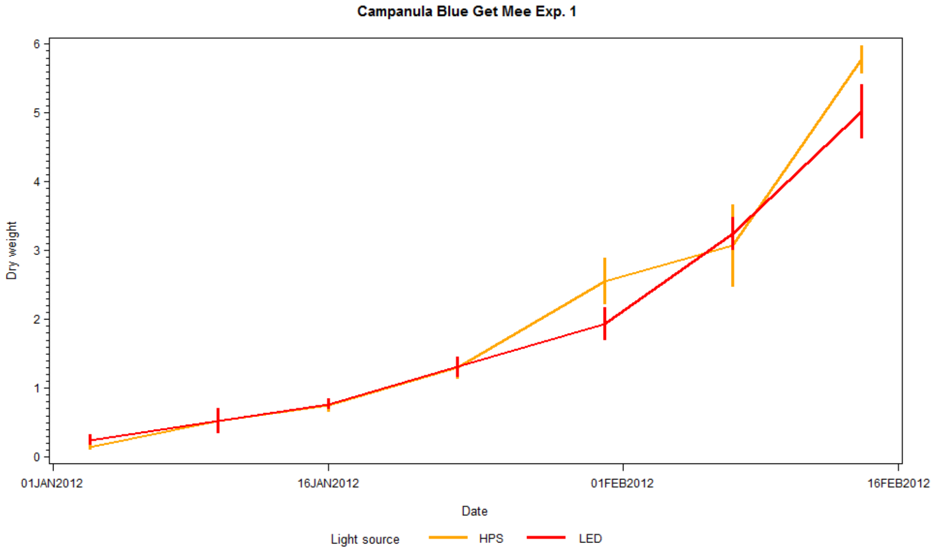


Figure 3: Trajectory of dry weight [g] of Campanula portenschlagiana grown under LED and HPS (Batch 1)

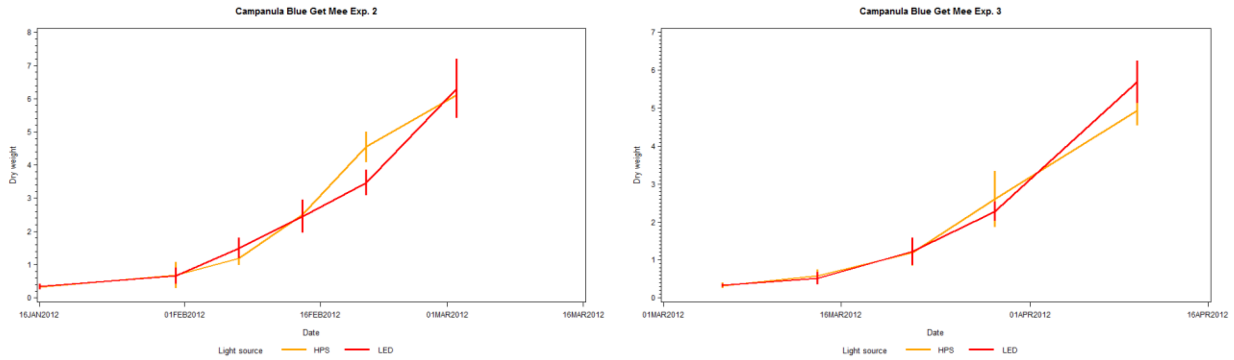


Figure 4: Trajectory of dry weight [g] of Campanula portenschlagiana grown under LED and HPS (batch 2 and 3)

6.4.1.2 Plant quality

An important factor in production of ornamental plants is the end quality of the product; because the marked price depends on the visual expression and that the product full fills some minimum and maximum requirements such as plant height.

Plants grown under LED did not change growth habit and were in large extend similar to plant grown under HPS.

Production time is another important factor, because a prolongation of production time increases energy consumption per plant but also reduces available production area over time. A reduction in released area owing to a delay in production time is jeopardising the production plan. Another negative effect is that pot plant trade is based on just in time production, because the plants cannot be stored. It is of great importance that plants can be delivered on time to satisfy the wholesale marked.

The plants were judge by three people individually and the same three persons judged all three batches of *Campanula portenschlagiana*. The conformation of persons who judge the plants came from core area such as sales department, breeding and production.

The plants were graded into five grades where the score of five was best.

In the first batch the development was faster under HPS. When approximately 40% of the plants produced under HPS reached the marketable stage, only 8 % has reached the same stage when grown under LED (Figure 5). The estimated delay of plant grown under LED was 4-5 days.

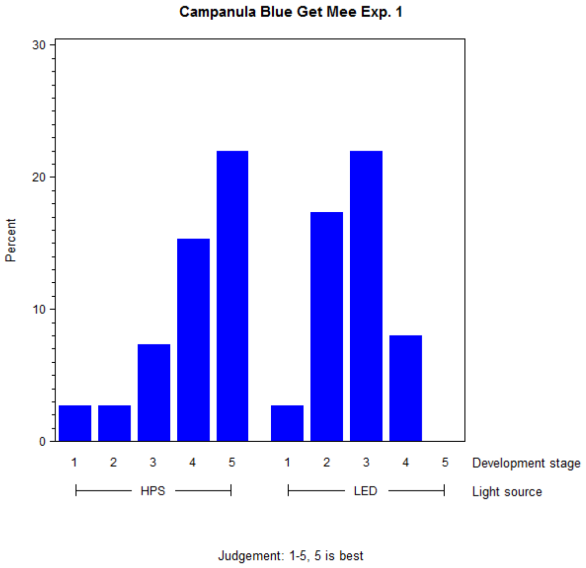


Figure 5: Grading of development at marketable stage (Batch 1)

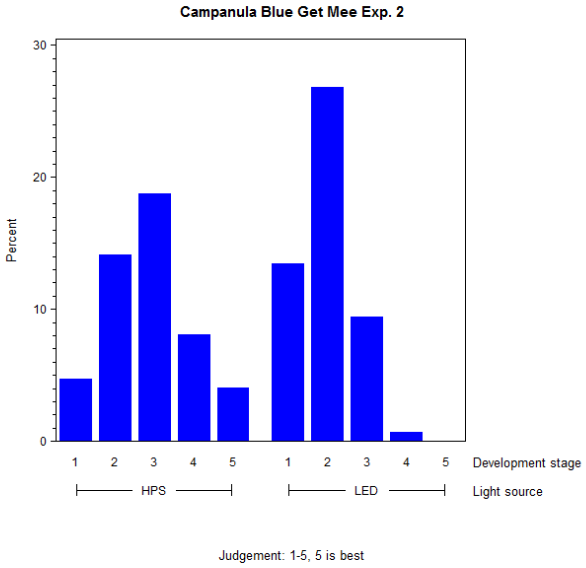


Figure 6: Grading of development at marketable stage (Batch 2)

In the second batch of plants the development under the two light sources was very similar to the first batch (Figure 6). The development was slower under LED and the production time was increased with three to four day. Under LED the development was more homogenous, this makes packing more easily, because few plants are left over owing to lesser development.

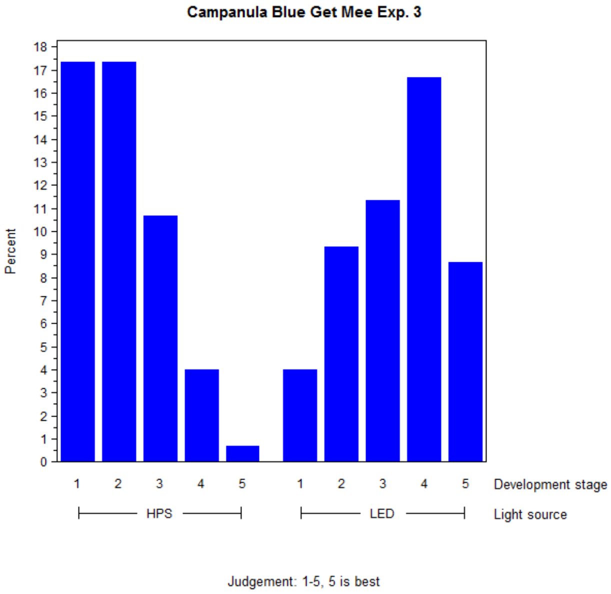


Figure 7: Grading of development at marketable stage (Batch 3)

In the third batch plants under LED was growing fastest and plants grown under HPS were 2-3 days behind in development (Figure 7). In the third batch the variation in developmental stage was the highest of the three batches of *Campanula portenschlagiana* grown under LED.

The number of inflorescences is an important quality factor together with plant shape and plant height. In

the quality judgement a visual estimation of inflorescences was used. The overall score of quality is a combination of number of inflorescences and plant shape. Light quality might influence both parameters, but no pronounced difference in shape and height was found between LED and HPS.

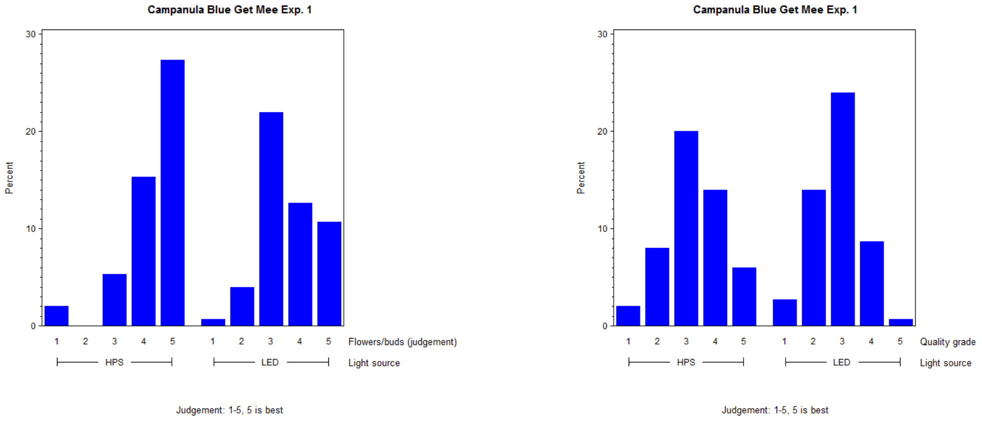


Figure 8: Visual estimation of inflorescences (left) and quality grad (right) for batch 1

In the first batch the overall quality of the plants was much better under HPS (Figure 8). It might have its origin in the number of inflorescences because significant more plants have a high number of inflorescences. Approximately 20 % of the plants grown under LED did not have a first grade quality against 10 % for plants grown under HPS.

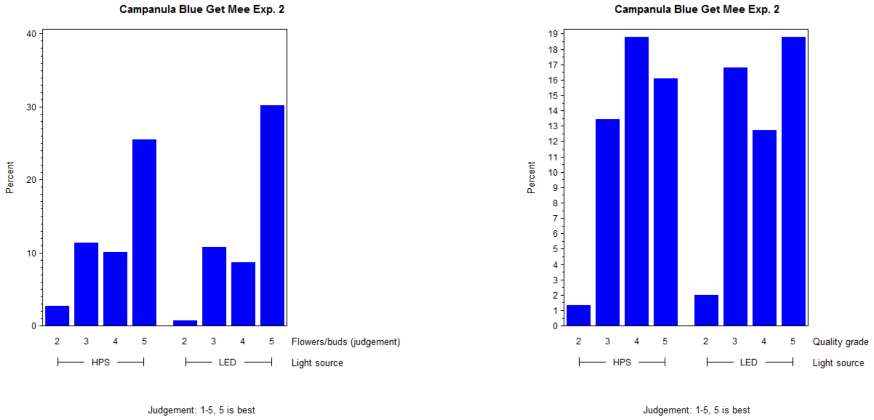


Figure 9: Visual estimation of inflorescences (left) and quality grad (right) for batch 2

In the second batch the number of inflorescences is nearly equal and with fewest plants in score 2 of plants grown under LED (Figure 9). There are no plants with a score of 1 in the overall judgement of quality for LED and HPS.

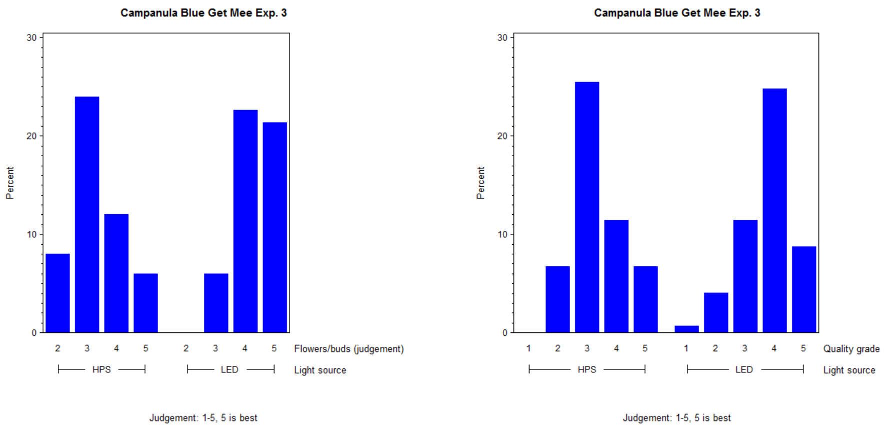


Figure 10: Visual estimation of inflorescences (left) and quality grad (right) for batch 3

In the third batch the number of inflorescences is highest at plants grown under LED which also is reflected in a higher quality (Figure 10). The percentage with a score of 3 in overall quality for plants grown under HPS is nearly equal to the percentage of plants with a score 4 grown under LED; which again is more than double for the same score under HPS.

6.4.1.3 Experiment 2

The delay in development during the period with lowest natural light was further investigated. The plants grown under LED were compared with plants grown in two other greenhouses than used in previous experiments to eliminate a greenhouse influence. The light intensity of HPS varied from LED and was either 10 µmol m^{-2}-s^{-1} higher or lower than LED.

The first batch of plants was grown in the period from middle of November 2013 to middle of January 2014. Plants grown under LED had a remarkably lower fresh weight measured at the marketable stage(Table 1)The production time was increased by 3-4 days for plants grown under LED.

Lampe type – Irradiance [µmol m-2 s-1]	Plant height [cm] Mean	Fresh weight [g] Mean	Dry weight [g] Mean	Dry matter content [%] Mean
LED – 130	11.4	49.3	6.7	13.6
HPS – 140	10.9	58.8	7.5	12.7
HPS – 120	10.7	53.1	6.6	12.4

Lampe type – Irradiance [µmol m-2 s-1]	Plant height [cm] Mean	Fresh weight [g] Mean	Dry weight [g] Mean	Dry matter content [%] Mean
LED – 130	11.4	49.3	6.7	13.6
HPS – 140	10.9	58.8	7.5	12.7
HPS – 120	10.7	53.1	6.6	12.4

Table 1: The influence of lamp type and irradiance on plant height, fresh and dry weight and dry matter content

The second batch of plants was grown in the period from beginning of December 2013 to the beginning of February 2014. Both fresh and dry weight of the plants grown under LED had significantly lower fresh and dry weight at the marketable stage compared with HPS (Table 2).

Lampe type - Irradiance	Plant height [cm] Mean	Fresh weight [g] Mean	Dry weight [g] Mean	Dry matter content [%] Mean
LED – 130	11.1	48.8	7.3	15.0
HPS – 140	11.3	58.1	8.5	14.7

Table 2: The influence of lamp type on plant height, fresh and dry weight and dry matter content

The production time showed same increase as in the first batch and the difference in development between LED and HPS is visible in figures Figure 11 and Figure 12.

Figure 11: The developmental stage of plants grown under LED at marketable stage. Plants in second batch

Figure 12: The developmental stage of plants grown under HPS at marketable stage. Plants in second batch

The increase in production time is similar in the two experiments and seems only to occur in the period where natural light is at the lowest. It might be to the spectral distribution and the so called Emerson effect could be the reason. Emerson found that that photosynthetic yield was lower for light in a single narrow band. Combining two narrow bands increased photosynthetic yield e.g. blue and red. What speaks against the Emerson effect is that there is no difference in dry matter content between LED and HPS.

Temperature plays an important role in plant growth, but the temperature differences between the greenhouses is very small and only in few days the temperature differ more than 1 °C in favour of HPS. Both LED and HPS contributes to the heating of the greenhouse and further information on the subject is described in the next section.

Campanula portenschlagiana is a long day plant, which means that it is only flowering when the day length longer than 14 hours. Light quality influences the plant recognition of day length, but red light promote flowering and the light intensity required to initiate flowering is very low. Both LED and HPS emit light in the red wavelength range and the intensity is far over the requirement for flower initiation. It is expected that the plant reaction is same for both lamp types and no delay in flowering should be expected.

Campanula portenschlagiana undergoes a change in morphology and the change occurs when the plant change from vegetative to generative phase. In the vegetative phase the growth habit is a rosette-shape dome. In the generative phase the plants is getting an erected habit when the vines are formed.

The spectral distribution might change the leaf angle which affects light interception and internal shade in the plant. A change in leaf angle might influence the amount of light and light quality that the developing vines receives. Under natural light conditions the far red wavelength range penetrates deeper into the plant canopy and courses stem elongation in vines. There is no far red light in the spectra of the LED but it is present in HPS. If the vines elongate faster under HPS it improves there light interception and the rate of development increases. This could be the reason for a faster development under HPS than LED under low natural light conditions.

6.4.1.4 Electricity and energy consumption

The use of energy for heating and electricity for artificial lighting was recorded. In the greenhouse with LED lighting was installed 224 LED fixtures with an energy consumption of 414 W each. In the greenhouse with HPS were installed 92 HPS fixtures with an energy consumption of 400 W each and 96 HPS fixtures with an energy consumption of 600 W. The electricity consumption for HPS is higher because the electromagnetic ballast and a 400 W fixture consume 465 W and 600 W fixture consume 770 W. The total electricity consumption is approximately 93 and 117 kW for LED and HPS respectively. The electricity consumption is 20 % less in the greenhouse with LED compared to the greenhouse with HPS. Exactly the same set points were use in the two greenhouses to control the artificial lighting, giving the same number of running hours.

Electricity consumption (MWh)	LED	HPS	Energy saving (%)
30th January – 2nd March 2012 (batch 2)	30.5	44.3	31
6th March – 10th April 2012 (batch 3)	30.7	43.8	30
30th January – 10th April 2012	64.0	92.1	31

Table 3: Electricity consumption

The energy saving is larger than the difference in installed electrical effect. HPS is consuming more power during start up, in contrast to LED which only has a where short peak (few seconds) at start up. The HPS

consumes nearly twice as much at start up compared to normal running condition. There is a minimum of one start up every day, and depending on natural light condition the artificial light might switch on and off a number of times.

6.4.1.5 Heating

The excess of heat from the fixtures will heat the greenhouse and the energy input from the heating system will be less. The HPS installation provides heat enough to heat the greenhouse as long as the outdoor temperature is higher than 8 °C at a set point of 20 °C. The LED installation is capable to provide heat enough at an outdoor temperature of 11 °C.

The energy consumption is not significantly increased by change from HPS to LED. Only in a short period (30th January to 16th February 2012) with diurnal outdoor temperatures down below freezing point and temperature down to -18 °C the energy consumption for heating was 20 % higher in the greenhouse with LED.

An artificial lighting system is considered as inefficient heating system because the heat is dissipated in the top of the greenhouse. The HPS fixture acts as a heating surface because of the high surface temperature and the warm air will raises to the top of the greenhouse envelope. When the artificial lighting system is running, a temperature stratification occurs with high temperature in the top of greenhouse. It is an unfavourable situation in regard to climatic control, because the temperature at plant level might be at the heating set point and the heating system delivers energy to the greenhouse simultaneously.

The surface temperature of a LED fixture is low owing to the active cooling. The air leaving the LED fixture has a temperature much closer to the surround airs and the fixture is not acting as a heating surface. The build in fan results in a mixing of outlet air into the surrounding air which reduces the stratification.

6.5 *Morphological responses*

6.5.1 Aim of the project

The primary aim of the project was to elucidate the effect of spectral composition on photosynthesis, photomorphogenesis, and secondary metabolism under the framework of the applicability of LEDs as a light source in greenhouse production. This report is a three-pronged approach (Experiments 1, 2, and 3) to comprehend major physiological responses, such as photosynthesis, stomatal conductance, chlorophyll fluorescence, secondary metabolism, and pigmentation from a lighting point of view focused on LEDs with a background of daylight.

Experiment 1 examined the effects of LEDs on net photosynthesis, stomatal conductance, morphological parameters, and secondary metabolites under four different light treatments in roses, chrysanthemums, and campanulas. It characterizes the effect of blue and red LED lighting, highlighting the significance of blue light in increasing stomatal conductance and the amount of phenolic acids and flavonoids. Measurements of total flavonoid content by non-invasive methods are compared with destructive procedures and evaluated.

Experiment 2 focused on the effect of LED lighting on growth, chlorophyll fluorescence, and pigmentation in two different *Phalaenopsis* cultivars that were grown under three different LED light treatments. Through the chlorophyll fluorescence parameters, we demonstrated that blue light is positively correlated with a decrease in quantum efficiency of PSII and a concomitant increase in the quantum yield of the down-regulatory non-photochemical quenching, although the effect was cultivar dependent linked to the inclination for red coloring of the leaf. We have also shown that the amount of carotenoids and chlorophylls is increasing with increasing amount of blue light.

In **Experiment 3** we tried to upscale the results from the previous experiments and investigated the effect of different blue LED light doses and its application time in green and red leaf lettuce. Blue LED lighting was applied to lettuce with distinct application times and intensities. We demonstrated the importance of blue light in increasing stomatal conductance and the amount of phenolic acids, flavonoids, and pigments. A timing and intensity effect of blue light application was also identified, and expressed through a decrease in the quantum efficiency of PSII and a concomitant increase in the quantum yield of the down-regulatory non-photochemical quenching. The results, though, were cultivar dependent.

6.5.2 Discussion of the results

6.5.2.1 LEDs variably affect growth, morphology, and development

Through photosynthesis, light constitutes the principal source of all forms of biological energy. Plant growth and morphogenesis is uniquely dependent upon light conditions, so plants utilize light directly in biomass production (Whitelam and Halliday 2007). Although radiant energies from wavelengths between 400 – 700 nm are utilized for the immensely significant process of photosynthesis, blue together with red light are predominantly absorbed by chlorophylls and other accessory pigments (Hart 1988). Our study was based on this premise and consequently we used different combinations of blue and red LED lighting to characterize the plausible effect on morphological and developmental characteristics. The photomorphogenic responses include, among others, modifications in plant height, leaf area, as well as fresh and dry mass.

In **Experiment 1**, we report that in roses, chrysanthemums, and campanulas different LED spectra affected plant height, leaf area, as well as fresh and dry weight (Appendix 1:Table 4). Both in roses and chrysanthemums, supplemental red light alone resulted in higher plant height. Red light has been reported to increase the leaf area in cucumber (Hogewoning et al. 2010). In roses, the treatments with the highest

amount of red light (20%B/80%R and 100%R) increased the leaf area more than the 40%B/60%R or the Control. On the contrary, in chrysanthemums, total fresh and dry weight was higher with increasing blue light portion. In campanulas, there was no difference between the treatments regarding total fresh and dry weight. This highlights the fact that the effects of blue and red light ratio are species dependent.

From a morphological point of view, we observed that roses and chrysanthemums demonstrated downwards leaf curling in the 100%R, while campanulas showed some petiole elongation. It has been reported that red light acting through phytochrome B is responsible for leaf curling (Inoue et al. 2008, Kozuka et al. 2011). The absence or limitation of supplemental blue light could have that effect as leaf flattening is controlled by the phototropins phot1 and phot2, since the background daylight was extremely low. The PKS2 and PKS1 genes act in the phot2 pathway and regulate leaf curling (de Carbonnel et al. 2010). It was suggested that phototropins promote leaf flattening by suppressing the leaf curling activity of the phytochrome B (Kozuka et al. 2013).

In **Experiment 2**, we showed that red light was mainly responsible for driving the fresh weight and leaf formation in *Phalaenopsis*. The results in fresh weight and leaf area were not the same for ‘Vivien’ and ‘Purple Star’, highlighting that the effects of blue light on plant biomass and morphogenesis are cultivar dependent. Supplementary blue light is required to sustain satisfactory growth and development of plants (Whitelam and Halliday 2007, Hogewoning et al. 2010). We also observed a more intense and earlier red coloration developing in the 40% B/R treatments for both cultivars, which could possibly be explained with the increasing amount of pigments. The cultivar ‘Vivien’ developed this characteristic red color earlier than ‘Purple Star’, illustrating the cultivar differences (Appendix 1: Table 4) that are also noticed in the commercial production of these two cultivars. These results indicate that light indeed plays a crucial role in determining fresh weight and leaf area of *Phalaenopsis*, nevertheless, also other factors such as leaf age, cultivar, or environmental conditions may in-fluence plant morphogenesis, making the spectral effects of LEDs on plant development a complicated phenomenon.

In **Experiment 3**, plant biomass was not affected by the blue light treatments in neither of the lettuce cultivars confirming earlier results (Dougher and Bugbee 2001, Yorio et al. 2001). All the plants under blue light had a compact appearance with no noticeable other morphological abnormalities. Specifically, no leaf curling was observed under blue light. As mentioned previously, blue light is perceived by the phototropins phot1 and phot2, which are responsible for regulating leaf flattening by suppressing the leaf curling activity of phytochrome B (Kozuka et al. 2013). Additionally, in lettuce, exposure to blue light could reverse morphological abnormalities and sustain a normal plant growth (Johkan et al. 2010). Our results indicate that lettuce grown under blue LED lighting did not enhance the fresh and dry weight, but rather partitioned assimilates for other processes, possibly the production of secondary metabolites.

6.5.2.2 Blue and red LED lighting increases stomatal conductance, but does not influence net photosynthesis

Net photosynthesis refers to the amount of gross photosynthesis minus the amount of respiration (Hart 1988). Stomatal conductance is closely related to net photosynthesis since stomata must be open in order for CO_2 to diffuse into the leaves. Hence, stomatal conductance and net photosynthesis are interrelated processes and are both affected by blue and red light. In **Experiment 1**, none of the species differed significantly among treatments with respect to P_n. As far as stomatal conductance is concerned, the regulation of stomata is influenced by both blue and red light; blue light acts as a signal and as an energy source through photosynthesis (Whitelam and Halliday 2007). A certain unspecified amount of blue light is important for not having a dysfunctional photosynthetic operation (Hogewoning et al. 2010). Blue light increased g_s in our investigation, but obviously this effect operated in the range when g_s was in excess of what was needed for supplying the plant with CO_2 because we observed no significant difference in P_n. The treatments with additional blue light caused stomata to open and demonstrated higher g_s, particularly in

roses and chrysanthemums (Appendix 1: Table 4).

It is worth mentioning that the increase in g_s by increasing blue light could be attributed to an additive or synergistic effect of stomatal traits, such as stomatal density, stomatal length, stomatal width, pore length or pore aperture (Boccalandro et al. 2012; Savvides et al. 2012). Additionally, we observed that g_s for campanulas was greatest in the 100%R (around 400 mmol m^{-2} s^{-1} while the Control was around 280 mmol m^{-2} s^{-1}) treatment at a PPFD of 200 µmol $m^{-2}s^{-1}$. Although one would not usually expect such high values, sometimes during the winter the relative humidity (RH) level can be rather high, and in species like roses it results in a reduced ability to close stomata (Giday et al. 2014), which could be a possible explanation for our results in campanulas.

In **Experiment 3**, increased amount of blue light clearly increased g_s, especially in green lettuce (Figure 13). The treatment with the highest blue light intensity (2B 17-19) was the one that had the highest value of g_s in both cultivars, though the effect was more prominent in 'Batavia'. It seems that high blue light intensity increased g_s. It has to be noted that our g_s measurements were taken between 09:00 and 14:00 when the blue LEDs were turned off, indicating the remaining effect of blue LED lighting on g_s. Sellin et al. (2008) has also shown increased g_s under high light intensity in silver birch. Other researchers have observed that supplying light at only 100 µmol m^{-2} s^{-1} for 16 h per day in cucumbers is sufficient to grow normal plants under different light spectra or blue and red LED light combinations (Hogewoning et al. 2010, Savvides et al. 2012). The current observations are possibly attributed to the involvement of phototropins and cryptochromes (blue light photoreceptors) in the regulation of g_s (Whitelam and Halliday 2007, Hogewoning et al. 2010).

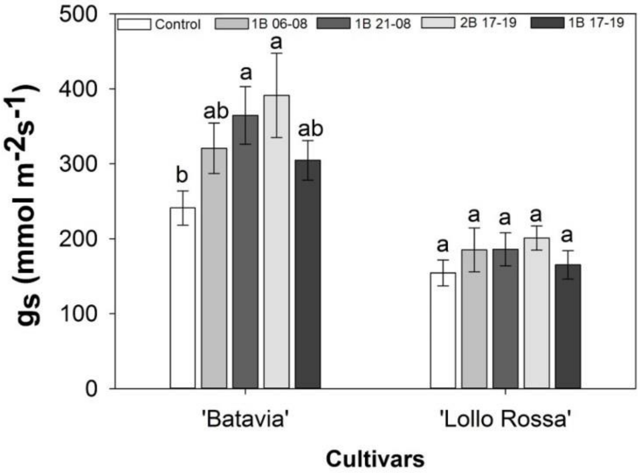


Figure 13: Stomatal conductance (gs) of Lactuca sativa cv. 'Batavia' and 'Lollo Rossa' grown under the five different LED treatments with the same abbreviations as in Figure 16. Data are mean values (n = 20) ± SE. Assignment of the same letters indicates values that are not significantly different at P-values < 0.05 within treatments.

6.5.2.3 LEDs affect chlorophyll fluorescence parameters, but the effect is species and cultivar dependent

As a non-destructive intrinsic tool, chlorophyll fluorescence has become a routine probe for information. Various aspects of photosynthesis are characterized by distinct chlorophyll fluorescence parameters. The maximum quantum efficiency of PSII, F_v/F_m, is on average 0.83 for 44 plant species of diverse origin (Björkman and Demmig 1987). A lower F_v/F_m value could be used as an indication of the stress level of plants, demonstrating possible photo-inhibition under stressful events (Maxwell and Johnson 2000, Baker and Rosenqvist 2004). In **Experiment 2**, F_v/F_m for *Phalaenopsis* was at lower levels, ranging from 0.52 to 0.72; however, this should not be a surprise as the parameter varies with species and environmental conditions (Björkman and Demmig 1987, Cha-um et al. 2010). The 0% B/R treatment showed the lowest

F_v/F_m value compared with the treatments that contained more blue. A small portion of blue light is essential to ensure a functional photosynthetic operation (Hogewoning et al. 2010). When plants were exposed to limited natural light in February, there were significant differences in F_v/F_m that were greater compared to March values, where ambient light and subsequently the portion of blue light was increasing. In **Experiment 3**, we observed values close to the optimal value when plants were untreated (under supplementary or natural light) or grown in combination with blue LED lighting. There was a slight lower value for the Control in comparison with the other treatments, which should not be interpreted as a stressful event since the decrease is so small that it does not have a biological significance for *Lactuca sativa*. However, the result concurs with the findings in *Phalaenopsis* by showing the lowest Fv/Fm in the treatment that was not enriched in blue.

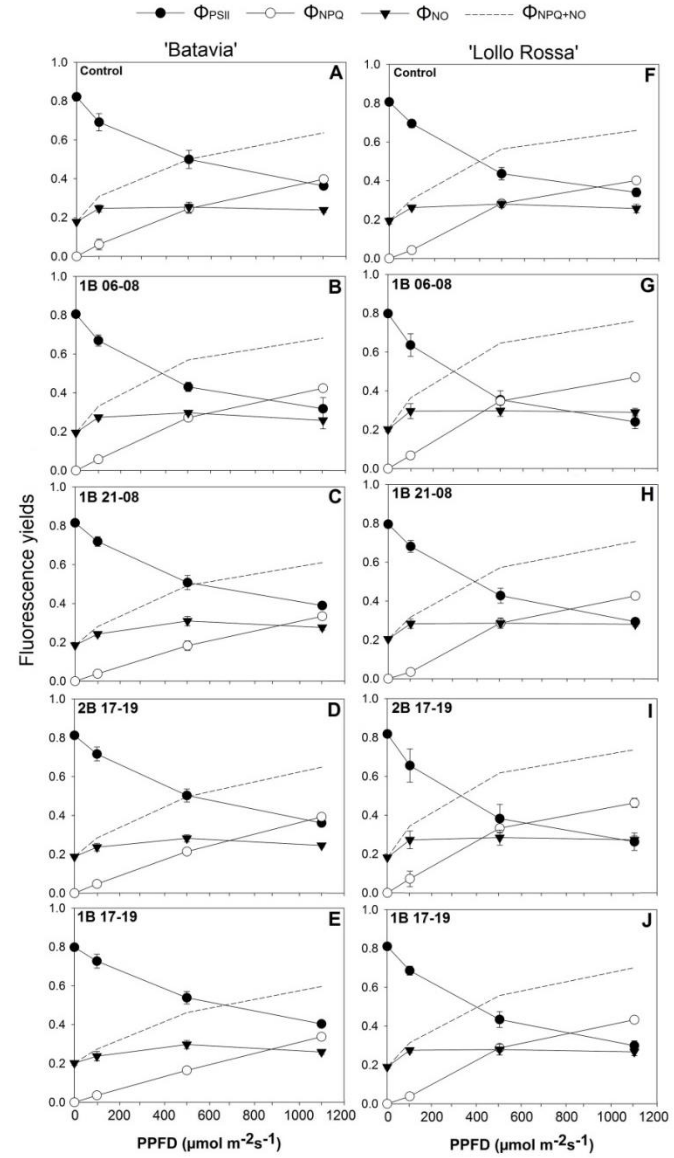


Figure 14: Quantum efficiency of PSII (ΦPSII), yield for dissipation for down-regulation (ΦNPQ), and yield of other non-photochemical losses (ΦNO) of Lactuca sativa 'Batavia' (A, B, C, D, E) and 'Lollo Rossa' (F, G, H, I, J) grown under the five different LED treatments with the same abbreviations as in Figure 16. Data are mean values (n=3) ± SE.

The amount of blue light applied seems to have an impact on Φ_{PSII} and Φ_{NPQ} with a different effect on two different *Phalaenopsis* cultivars as well as on green and red leaf lettuce (Appendix 1: Table 4). In **Experiment 2**, in 'Purple Star' there was no significant difference in the balance between these two yields

and the light level where Φ_{NPQ} crosses Φ_{PSII} was in the range of 510-620 µmol m^{-2} s^{-1}. In 'Vivien' the difference found in NPQ is reflected in a corresponding difference in Φ_{NPQ}, which changes the light level where the two curves cross from 120 µmol m^{-2} s^{-1} in the 40% B/R to 490 µmol m^{-2} s^{-1} in 0% B/R. In **Experiment 3**, Φ_{PSII} in the Control treatment in green lettuce did not show any substantial difference from the blue light treatments and at the same time there was no increase in the Φ_{NPQ} (Figure 14). These results indicate that additional blue light does not affect much the Φ_{PSII} and Φ_{NPQ} of green lettuce. On the other hand, red lettuce showed a shift to lower PPFDs in all the blue light treatments with the intersection points of Φ_{PSII} and Φ_{NPQ} occurring at an earlier range of 500 to 800 µmol m^{-2} s^{-1} in comparison to the Control (950 µmol m^{-2} s^{-1}). The additional amount of blue light triggers a decrease in Φ_{PSII} and a concomitant increase in the Φ_{NPQ} and the heat dissipation from PSII (NPQ). These mechanisms are employed by the plants to protect the leaf from possible light-induced damage (Maxwell and Johnson, 2000). Moreover, 1B 06-08 again had the strongest effect on Φ_{PSII} illustrating that a predawn (from 06:00 to 08:00) application of blue light might affect the quantum efficiency of PSII more than a post dawn application.

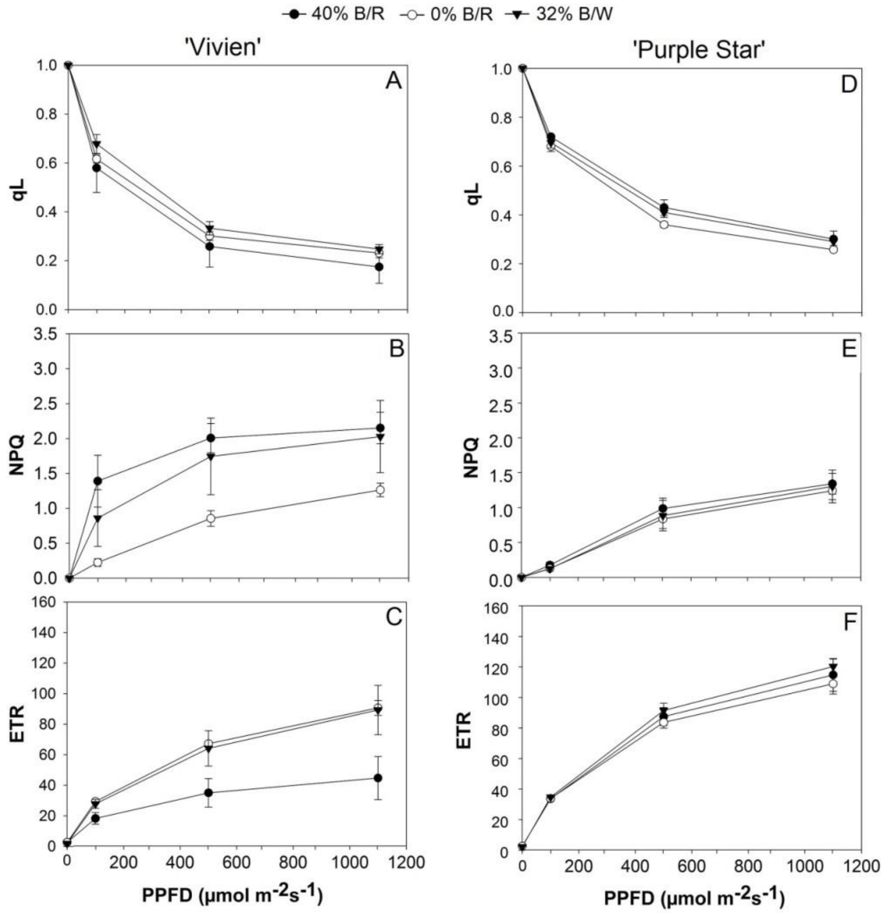


Figure 15: Fraction of open PSII centres (qL), non-photochemical quenching (NPQ), and electron transport rate (ETR) of Phalaenopsis 'Vivien' (A, B, C) and Phalaenopsis 'Purple Star' (D, E, F) grown under the three different LED treatments: 0% B/R, 32% B/W, and 40% B/R. The measurements were conducted in late March. Data are mean values (n=3) ± SE.

In **Experiment 3**, in the red lettuce, ETR was lower for the blue LED treatments compared to the Control values. Specifically, these observations were more prominent in the predawn (1B 06-08) or the double intensity (2B 17-19) applications, indicating that application timing and intensity is important for the ETR of red lettuce. It is also worth noting that we performed the measurements with the internal light source of a fluorometer, hence our results show a remaining effect of the blue light applications on the plants after the different treatments and this was expressed with lower ETR and Φ_{PSII} values. The reduction of the Φ_{PSII} under blue light could be attributed to changes in the energy distribution between photosystems (Evans

1986). Loreto et al. (2009) reported that ETR increased for *Platanus orientalis* with increasing blue LED lighting (40% and 80% blue), but decreased for *Zea mays*, demonstrating that the effect could also be species or cultivar dependent. Similarly, the effects on all the aforementioned parameters were not observed in the two cultivars the same way, highlighting the fact that chlorophyll fluorescence responses are cultivar or species dependent. Moreover, in **Experiment 2**, we have also shown that two different cultivars of *Phalaenopsis* behaved differently when we measured the same parameters (Appendix 1: Table 4). The photosynthetic parameters of the two cultivars had different responses to the three supplementary light treatments when measured by chlorophyll fluorescence using the internal lamp of the fluorometer (i.e. with the same spectral composition during measurements). 'Vivien' showed different ETR and NPQ to the two extreme treatments 0% B/R and 40 % B/R, while the 32% B/W treatment lingered in the middle without showing no significant difference to any of the B/R treatments (Figure 15). The lowest ETR in 40% B/R 'Vivien' was accompanied by the highest NPQ even though the oxidation state of PSII (q_L) was unaffected. At the same time, 'Purple Star' was completely unaffected by the treatments, illustrating again that the acclimation of photosynthesis to light of different spectral distributions is both species and cultivar dependent.

6.5.2.4 Blue light increases phenolic acid, flavonoid, and pigment content

Light acts as a signal through which a plant can receive information about its environment and acclimate accordingly. We found a large number of phyto-chemical compounds to be involved in the acclimation of plants to their light environment. Blue light was responsible for triggering an increase in the amount of phenolic acids, flavonoids, and pigments. The functions of SMs have been extensively under research the last century. For instance, chlorogenic acid, p-coumaric acid, kaempferol glucoside, rutin, quercetin, and apigenin glucuronide show antimicrobial, antioxidant, antifungal, antigenotoxic, and radical scavenging activities (Seigler 1998, Kefeli et al. 2003, Lattanzio et al. 2006, Wink 2010). In **Experiment 1**, we found these phenolic compounds increased by the exposure to increasing blue light fraction (Appendix 1: Table 4). Phenolic acids and flavonoids constitute two of the most ubiquitous groups of SMs in plants and represent an example of metabolic plasticity enabling plants to adapt in biotic and abiotic environmental changes (Lynn and Chang 1990, Wink 2010). The treatments with the highest blue light ratio were also the treatments with the highest amount of SMs. This means that plants grown under higher blue ratio did not enhance vegetative growth, but rather partitioned assimilates for production of SMs. The production of SMs in plant tissues such as leaves is regulated by an interaction of environmental, physiological, biochemical, and genetic factors (Wink 2010). The light environment is one of the most influential factors for the plant secondary metabolite production (Kopsell et al. 2004, Kopsell and Sams 2013) and exposure to varying wavelengths trigger physiological changes (Samuolienė et al. 2013). In roses and chrysanthemums, the treatment that triggered the highest production of SMs was the 40%B/60%R, while in campanulas it was the 20%B/80%R. This indicates that different plant species respond individually to the amount of blue light.

In **Experiment 3**, we reported that the amounts of chlorogenic acid, caffeic acid, chicoric acid, anthocyanin, quercetin glucuronide, and quercetin malonyl glucoside were higher in all blue LED treatments compared to the Control, especially in red lettuce. It is not clear which blue light application time triggers a greater effect, but this highlights the fact that blue light is involved in the production of SMs. However, the production might be influenced in an in-dependent manner depending on the amount of additional blue light. The effect, though, is more prominent in red lettuce, indicating a possible eco-physiological adaptation where the red coloration holds information that affects both visible pigments and the energy balance of photosynthesis. In addition, 1B 06-08 demonstrated the highest amount of all the phenolic compounds, which also had the ETR. This indicates that a blue LED application in the early morning could create a possible stressful event that will probably induce the accumulation of phenolic compounds. In green lettuce, this phenomenon could be attributed to a reduction in the growth of lettuce grown under

blue LED treatments. Regarding the mechanism behind the induction of SMs, Heo et al. (2012) reported that the activity of phenylalanine ammonia-lyase (PAL), which is a key enzyme in the phenylpropanoid pathway, was stimulated by blue LED irradiation. In addition, Son et al. (2012) have shown that PAL gene expression was activated by monochromatic blue LEDs in lettuce. Consequently, blue light is possibly involved in the activation of the biosynthetic pathway for these phytochemicals.

Plant pigments receive substantial research attention due to their significant involvement in light harvesting activities and stress physiology. Carotenoids are red, orange or yellow pigments providing protection when plants are overexposed to light via dissipation of excess energy and free radical detoxification (Lattanzio et al. 2006, Wink 2010). Moreover, their contribution to photosynthesis is clear through harvesting and transferring light energy to chlorophyll molecules (Davies 2004, Frank et al. 2004). In **Experiment 2**, we demonstrated that treatments with additional blue light increased the content of violaxanthin, lutein, and β-carotene (Figure 16, Appendix 1: Table 4). Violaxanthin is crucial as under excessive light (in our case additional blue) is de-epoxidised to zeaxanthin via antheraxanthin and under low light zeaxanthin is again epoxidised to violaxanthin (Li et al. 2000). This process is part of the NPQ-mediated dissipation of excess absorbed energy, which possibly limits the formation of chlorophyll triplets and prevents the reactive oxygen species from being produced (Demmig-Adams and Adams 1992). Lutein and β-carotene are also key components of the light-harvesting complex (LHC) of leaves. In our study, we found lutein in greater amounts than any other carotenoid or chlorophyll. In addition, β-carotene content increased with increasing blue light. This suggests that the additional blue light triggered the photoprotective role of lutein and β-carotene by increasing their amount. Lutein was highest for the 40% Blue and β-carotene was mostly highest for the 32% Blue of *Phalaenopsis*, indicating that the amount of blue light needed for increasing such carotenoids depends also on the pigment itself. Lutein absorbs blue light and appears yellow at low concentrations and orange-red at high concentrations; β-carotene is a red-orange pigment (Krinsky et al. 1989, Davies 2004, Frank et al. 2004). This could be an explanation for the early red coloration we observed in the 40% Blue treatment, first in *Phalaenopsis* ‘Vivien’ and later in *Phalaenopsis* ‘Purple Star.

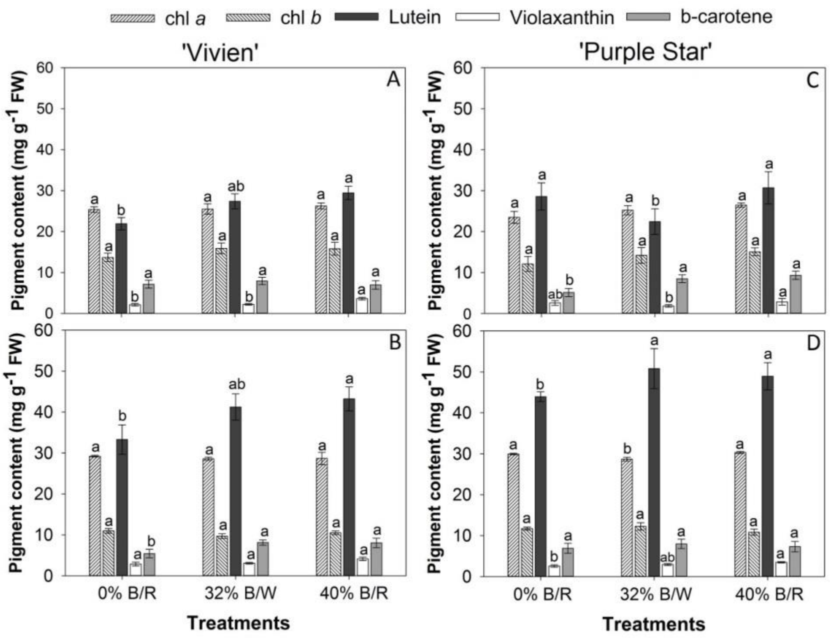


Figure 16: Pigment content (chl a, chl b, lutein, violaxanthin, and β-carotene) in March of (A) 1st and (B) 2nd developing leaf of Phalaenopsis ‘Vivien’ and (C) 1st and (D) 2nd developing leaf of Phalaenopsis ‘Purple Star’ grown under the three different LED treatments: 0% B/R, 32% B/W, and 40% B/R. Data are mean values (n=5) ± SE. Assignment of the same letters indicates values that are not significantly different at P-values < 0.05 within pigments.

In **Experiment 3**, depending upon the cultivar, the chlorophyll and carotenoid content varied in lettuce, but in general all pigments increased their amount with additional blue light. Indeed, we identified chl *a*, chl *b*, neoxanthin, violaxanthin, zeaxanthin, lutein, and β-carotene at higher amounts under the blue LED treatments. Blue light is important for chlorophyll formation, so the additional amount of blue is absorbed and utilized to increase their concentration. Xanthophylls and carotenes are major classes of carotenoids. In addition to the previous mentioned carotenoids, neoxanthin is also an important xanthophyll, being an intermediate in the biosynthesis of abscisic acid (Davies 2004).

6.5.2.5 Light stress and plants

Light interacts with biological processes in a variety of ways and depending on the species and cultivars irradiation could trigger stressful or non-stressful events for plants. In our study, we reported an increase in the phytochemical content, when plants were exposed to different blue and red LED light treatments. Depending on cultivars and species, plants interpret the change in their light environment differently and respond in a distinct mode. For example, in **Experiment 1**, the effect of blue and red LED lighting on phenolic acid and flavonoid content was more prominent in the 20%B/80%R treatment for campanulas, whereas in roses and chrysanthemums the effect was more influential in the 40%B%60%R treatment. In **Experiment 3**, blue light showed a high correlation with the production of phytochemicals in red lettuce; however, the effect was very limited in the green lettuce. Secondary metabolites act as defence and signal compounds, as well as protectors from UV radiation and oxidants (Wink, 2010). Plant phenolics have key roles as the major blue and red pigments, antioxidants, as well as protectants from UV radiation. Therefore, their established roles are clearly ecological in nature. UV radiation induces the production of reactive oxygen species (ROS) and plants protect themselves from harmful radiation by synthesizing phenolic acids and flavonoids, acting as a screen inside the plant cell (Kaiserli and Jenkins 2007, Jenkins 2009). For instance, the amount of SMs is enhanced under UV-B radiation in carrots (Gläβgen et al. 1998) and grapes (Pezet et al. 2003).

While UV-B is sensed by the UVR8 photoreceptor (Kaiserli and Jenkins 2007), blue and UV-A light share the same photoreceptors, the phototropins (Cashmore et al., 1999; Lin and Shalitin 2003). The cryptochromes and the UVR8 are involved in the production of SMs. After exposure to UV-A, UV-B or blue light, flavonoids are produced in the epidermal layers and trigger activity of the antioxidant systems (Kaiserli and Jenkins 2007, Jenkins 2009, van Buskirk et al. 2012). Ultraviolet B and blue light exposure mediate defence signalling pathways that lead to gene expression under stress or eustress (Hideg et al. 2013). In addition, the spectral composition from LED lighting cannot be found in nature. By artificially strengthening the blue signal, it could act as a precursor for alternate or stressful conditions. When a plant experiences a change in growth conditions (not necessarily stressful conditions), defence genes are expressed. In our study, blue light is possibly causing a eustress and the increasing amount of the blue light fraction predisposes the plants to a state of low alert that includes the increase of SMs as a defence mechanism. A low dose of UV-B has similar effects (Hideg et al. 2013); hence the same effect might be obtained either with UV-B radiation or blue LED lighting.

6.5.3 Project Contribution

The main emphasis of this project is on the physiological, photosynthetic, and chemical acclimation of four greenhouse plants in response to different spectral environments. We hope this thesis to be a seminal document for advancing the research in the specific field. The substantial information derived from this thesis could be summarized in the following points:

1) LED lights with high proportion of blue (20%B/80%R and 40%B/60%R) did not deteriorate or even enhanced growth and morphological aspects in rose, chrysanthemum, campanula, and *Phalaenopsis* plants. The effects in biomass production, though, are species and/or cultivar

dependent. Similarly for the effect of the different blue dose responses in lettuce plants. Such lighting strategies and at the appropriate intensity could be implicated from growers with no concerns for plant stress.

2) Blue light alleviates morphological abnormalities such as leaf curling and therefore it is an important constituent to retain a functional photo-synthetic apparatus, in combination with red light.
3) Blue light increased stomatal conductance of rose, chrysanthemum, and lettuce plants. The use of blue light to improve stomata function is an important observation that can be used from growers in periods of low natural daylight to improve the physiological performance of plants.
4) Chlorophyll fluorescence measurements could be used as a significant tool for measuring the photosynthetic performance of Phalaenopsis and lettuce plants grown under LEDs. Blue light affects the quantum efficiency of PSII and the yield of non-photochemical quenching. Consequently, these measurements are an indication for possible environmental changes or even stressful events that can occur during plant growth.
5) LED-grown plants increased the amount of secondary metabolites and pigments with increasing blue light ratio. Blue light seems to trigger the biochemical defence of the plants since it regulates the production of these compounds. Hence, blue light preconditions the plants to cope better with stress and light changes in their growing environment.
6) The timing of application, the intensity, and the amount of blue light needed is an on-going discussion and depends on cultivation conditions and plant species.
7) The effects of LEDs on photosynthesis and secondary metabolism were species and/or cultivar dependent. Plants that exhibit sensitivity in these specific photosynthetic and chemical measurements and show concomitant responses might be less tolerant than other plants under the same light regimes.
8) Growers could use non-invasive Dualex measurements as an indication for flavonoid content in roses, chrysanthemums, and campanulas. However, the optical properties of the leaves should be taken into account as measurements would vary due to leaf thickness. To ensure proper measurements, Dualex measurements should be accompanied by destructive chemical analysis.

6.5.4 Future work

Although astonishing research progress has been made over the past several years with the advent of LED lighting in greenhouse facilities, much remains to be done. The coming decades will offer exciting advances as we probe for a deeper understanding of photomorphogenesis, photobiology, and chemical biosynthesis in greenhouse plants grown under LEDs. This work has also revealed potential research gaps requiring further research and there is still much to learn. Possible questions and suggestions include:

1) Application of different blue and red LED light combinations on different species and cultivars. Is there a magic percentage of blue/red ratio for optimal growth?
2) Closer scrutiny of net photosynthesis by gas exchange measurements. Perhaps measurements in growth chambers could help exclude para-meters such as humidity fluctuations in the greenhouses and provide more reliable measurements.
3) How do stomata open in response to blue light and how many factors are affecting this outcome? What is the role of the photoreceptors and which ones are involved? Further investigation is also needed to determine the possible common effect of blue and UV-A or UV-B

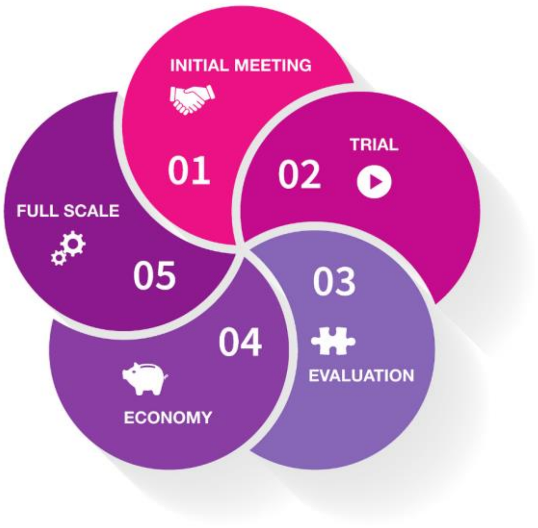
photo-receptors.

4) What is the mechanism behind the increase of secondary metabolites with increasing blue light? What is the nature of this signalling work? What genes are involved in this biosynthesis? The molecular approach in connection with the physiology could provide meaningful insights.
5) Quantification and identification of primary and secondary metabolites in response to blue LED lighting. Is there a trade-off between them?
6) Given the industrial nature of the project, a possible recommendation for northern latitudes would be a light source that provides sufficient blue light while maximizing energy efficiency.

7. Utilization of project results

7.1 Senmatic/Fionia Lighting

This project has resulted in a joint venture between Fionia Lighting and Senmatic meaning that Senmatic will now produce, distribute and sell the FL300 fixtures from Fionia Lighting. This arrangement is made for two main reasons. An easy access to a global distributor network for Fionia Lighting with an increase in revenue as a result, and an access to a Danish factory which are approved with ISO standards. Senmatic can add another high tech product to their range of product already applicable to the greenhouse sector such as climate computer, fertilizer mixing and irrigation control. Senmatic expects to market this all over the world making appearances on fairs and securing new dealers especially for the light system. The business plan has been updated, and we now follow the below strategy for "go-to-market":



Initial meeting

The first stage in the process is the initial meeting, in which the grower and the FL300 representatives get together to discuss solution requirements. These include aspects such as crop, location, light, application, and expected outcome, etc. The initial meeting prepares the customer for the upcoming stages, leaving him/her confident about the overall process.

Trial

We always recommend an initial trial for all but well-tested and documented crops. Depending on greenhouse geometry, crop, and light requirements, we establish a trial area ranging from 10-100 fixtures including light control. This area enables customers to evaluate different light recipes and intensities for a specific crop in a specific greenhouse. A well-executed greenhouse trial answers ten times as many questions as a closed room investigation at a light provider.

Evaluation

We are present during and after the trial to assist with adjustments and recipe advice – not only for light but the other factors involved in a trial. When it comes to evaluation, focus on energy savings is important but it is also vital to evaluate every aspect of greenhouse production. For example, did the crop maintain the same quality as previous crops; is the number of tomatoes harvested sufficient; was there a reduction in chemical usage, and so on.

Economy

There are always two sides to the economy equation: Does the installation result in sufficient savings - and can I finance it? In some installations, our system pays for itself within three years, and our prices are now highly competitive with conventional lighting.

Financing greenhouse equipment can be complicated and we can provide assistance during the process. We offer customized, complete calculations for every aspect of the solution. There is also a variety of financing options available for full-scale installations.

Full Scale

On successful completion of the first four stages, we are ready to move into the final stage: the full-scale greenhouse installation. During this stage, we always recommend that we implement the final LCC4 light control installation to ensure optimal performance. At Fionia Lighting, we are guided by our philosophy of never leaving a new installation before everything works and the grower is happy.

7.2 PKM

As one of Scandinavia's largest flower nurseries, PKM was seeking a solution to maximise electricity savings while maintaining a high plant quality. To achieve this, they have tested and demonstrated FL300 with the following results:

For four growth seasons, PKM has tested the FL300 system. In 2011/2012 more than 100,000 Campanula flowers were grown with the following results:

- Up to 50% electrical saving compared to 400 watt HPS system
- Up to 35% electrical saving compared to new 1,000 watt HPS system

As a result of the results of the demonstration site PKM decided in 2014, that the installation was expanded by 1500 m2, making it one of the biggest LED top light installations in the world.

Utilising more energy than 25.000.000 kWh every year on lighting, they are focused on saving as much energy as possible, resulting in an improved earnings pr. plant produced.

7.3 University of Southern Denmark

Please see results section under morphological responses.

8. Project conclusion and perspective

This project was a result of joined forces from industry, a customer and the research community which in the end resulted in a commercial applicable result that hopefully will result in increased revenue and an increase in employees for the Danish industry.

The main objection with this project was to build a demonstration site with a Danish grower that demonstrated three main things: The fixture, the intelligent control and the know-how that surrounds the technology. The demonstrations site has now been working for three years, and we have had customers from all over Europe visiting and learning about the technology and the challenges of this new technology.

Our approach to the growers is, unlike other competitors, a two way street. We come with a highly complex fixture with a strong control system that is low cost. Our strategic corporation with Osram enables us to deliver high quality and possibilities without having a price that scares customers away. On the other hand, and one of the true benefits of this project, we are able to supply knowledge of integration and plant response on top of a good product. This combination of customer and research insight provided during this project is of high value to the project, and we recommend more projects with this specific category of interests.

During this project it was necessary to establish a novel business plan for the growers, meaning that the implementation was observed slower than expected. Each grower has to first witness a demonstration site in action, then trial 10-50 fixtures for himself before he makes large investments. We had initially hoped to skip the middle step, but as the market is now it looks like a steady stable implementation.

In terms of future projections we are optimistic, although we are in market that is not thriving. The greenhouse sector is not having its best years, and apart from a few main cultures they are all losing money at the moment. We believe that, with this project and demonstration site, we can establish a position in a top five position within LED lighting for horticulture in the world.

Appendix

Appendix 1: Table with plant responses

LED treatments	Species	Response
100% Red	Rose	Leaf curling, increased leaf area, plant height, and fresh and dry weight.
100% Red	Chrysanthemum	Leaf curling, increased plant height.
100% Red	Campanula	No apparent morphological abnormalities observed.
20%Blue/80%Red	Rose	Increased number of green buds and alleviated morphological abnormalities.
20%Blue/80%Red	Chrysanthemum	Increased mostly the leaf area and fresh and dry weight. Net photosynthesis was slightly enhanced but did not differ statistically. Stomatal conductance increased the most under this treatment.
20%Blue/80%Red	Campanula	Increased leaf area and fresh weight. The amount of phenolic acid content increased more than the 40%B/60%R.
40%Blue/60%Red	Rose	Net photosynthesis was not affected. Stomatal conductance increased as well as the amount of phenolic acids and flavonoids.
40%Blue/60%Red	Chrysanthemum	Net photosynthesis was slightly enhanced but did not differ statistically. Stomatal conductance increased, but less than the 20%B/80%R. The amount of phenolic acids and flavonoids was increased the most.
40%Blue/60%Red	Campanula	Net photosynthesis was not affected. Stomatal conductance increased more than the 20%B/80%R. The amount of phenolic acids increased but less than the 20%B/80%R.
0%Blue (100% Red)	*Phalaenopsis* 'Vivien'	Demonstrated lower F_v/F_m in the winter months.
0% Blue (100% Red)	*Phalaenopsis* 'Purple Star'	Increased fresh weight and leaf area when plants were eight weeks old. The effect was attenuated four weeks later.
40%Blue/60%Red	*Phalaenopsis* 'Vivien'	Developed earlier red coloration, increased NPQ and Φ_{NPQ}, but decreased ETR and Φ_{PSII}. Increased pigment content.
40%Blue/60%Red	*Phalaenopsis* 'Purple Star'	Did not affect NPQ, ETR, Φ_{PSII}, and Φ_{NPQ}. Increased pigment content.
1B 06-08, 1B 21-08, 2B 17-19, 1B 17-19	Green lettuce 'Batavia'	Fresh and dry weight was not affected. 1B 06-08 enhanced leaf expansion and plants grown under 1B 21-08 and 2B 17-19 were more compact. Stomatal conductance was substantially increased. Fluorescence yields were not affected. Slightly enhanced the content of phenolic acids, flavonoids, and pigments.
1B 06-08, 1B 21-08, 2B 17-19, 1B 17-19	Red lettuce 'Lollo Rossa'	Fresh and dry weight was not affected. 1B 06-08 enhanced leaf expansion and plants grown under 1B 21-08 and 2B 17-19 were more compact. Stomatal conductance was slightly increased. Increased Φ_{NPQ} and decreased Φ_{PSII}. Significantly increased phenolic acid, flavonoid, and pigment content.

Table 4: Plant responses to different LED light treatments used in this study

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Appendix 3: List of publications

1.1 Advertisements

01-2013	Gartnertidende – IPM 2013
05-2013	Flora Culture – LCC4 + LED
05-2013	Gartnertidende – LED
08-2013	Greenhouse Growers – Four Oaks + LCC4 + LED
01-2014	Gartnertidende + Greenhouse Growers – IPM 2014
05-2014	Gartnertidende – GreenTech 2014

1.2 Refereed articles in scientific journals and conference proceedings

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Ottosen, CO. 2013.

How to save on supplementary lighting. LED or SON-T? Greengrowing Workshop, 8 March , Stavanger, Norway

Ottosen, CO. 2013.

How to save on supplementary lighting. LED or SON-T? HDC, STC, UK

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LED and dynamic light. Presentation Agrifood Research Finland MTT in Turku 14 jan 2014

Hansen, Michael Jørgen; Nyord, Tavs; Hansen, Line Block; Martinsen, Louise; Hasler, Berit; Jensen, Peter Kryger; Melander, Bo; Thomsen, Anton Gårde; Poulsen, Hanne Damgaard; Lund, Peter; Sørensen, Jørn Nygaard; Ottosen, Carl-Otto; Andersen, Lillie. DCA - Nationalt center for fødevarer og jordbrug, (2013)

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