IMPROVED HEALTHY GROWTH OF BASIL SEEDLINGS UNDER LSC FILTERED ILLUMINATION

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ABSTRACT: Luminescent Solar Concentrators (LSCs) have the potential for use in greenhouse roof panels to produce electricity while increasing agricultural productivity. Given that LSCs do not exhibit a perfect light trapping, part of the fluorescence light exits through the escape cone enriching the transmitted spectrum in the fluorescence band. This work concerns the evaluation of LSCs as modular devices for greenhouse building hence both the performances of LSC modules as well as the influence of this devices on basil seedlings growth was assessed. The LSC prototypes evaluated showed efficiencies ranging from 1.23 to 0.85% which, given the large surfaces involved by greenhouses, are sufficient to provide ventilation or provide water pumping. Basil seedlings were grown for three weeks under different LSC covers which in the case of red dyed LSC resulted in improved growth and health comparing to the seedlings grown under transparent PMMA

Keywords: AgroPV, Concentrators, Devices, Stand-alone PV Systems, Water-Pumping

1 INTRODUCTION

Luminescent Solar Concentrators (LSCs) have the potential for use in greenhouse roof panels to produce electricity while increasing agricultural productivity.

This potential comes from the intrinsic inefficiency of the light trapping inside the device which depends on the transparent medium of choice.

Indeed, while 75% is trapped inside the transparent medium, approximately 25% of the fluorescence light is lost through the escape cone 12.5% from each side of the device, the net result of this emission is the enrichment of transmitted light in the fluorescence band of the dye.

Photosynthesis in plants is performed mainly through two pigments (*chlorophyll a* and *chlorophyll b*) that absorb strongly in the red and blue regions giving plants their green colour.

LSCs, therefore can convert part of the green light unused by plants into red light increasing their photosynthetic efficiency which could result in an improved growth health.

LSCs in greenhouses, then, could not only provide power for the ventilation and pumping systems but also promote the growth of the cultivated plants.

2 LUMINESCENT SOLAR CONCENTRATORS

2.1 Self-Absorption

Once exposed to sunlight, fluorescent dye molecules absorb a fraction of the incoming light then re-emitting it isotropically at longer wavelengths (fluorescence phenomenon).

In LSCs this phenomenon is used to trap and guide the trapped light towards the sides of a transparent slab where it is collected by solar cells to produce electricity.

A typical greenhouse cover is made of double-wall PolyCarbonate (PC) panels with dimensions of roof panels ranging from 0.6x3m^2 to 1.2x3m^2, because of this considerable size the fluorescence light emitted from the dyes within the LSC has to cross long distance before being absorbed by the solar cells.

Unfortunately, fluorescent dyes present an overlap between the absorption and emission spectra, this overlap leads to a phenomenon known as self-absorption which has a strong impact on the performances of LSCs because causes multiple absorption-emission events that reduce the light transport efficiency.

The study of the self-absorption of the spectral components of the emitted light is therefore crucial to forecast the electrical efficiency of LSCs featuring this dimension, in particular the larger ones as the devices of interest in this work.

The spectrum of light reaching the cells has been studied shining a small portion of the LSC through a circular aperture at increasing distance with respect to the solar cells array.

This data can be also used to calculate the absorption coefficients and the half-power length for the photons at various wavelengths in the different samples.

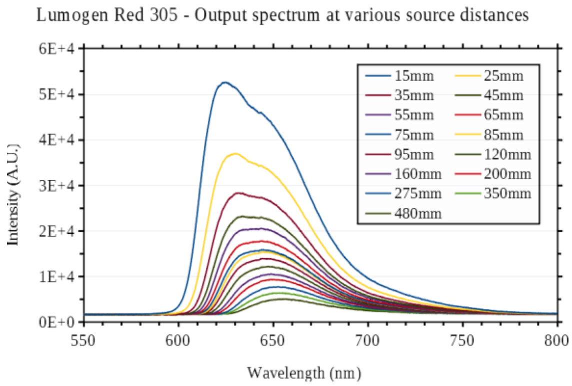


Figure 1: spectrum emitted from the side of a 160ppm red LSC at increasing stimulation distance

The test has been carried out on 0.5x0.5m^2 LSC slabs, functionalized with Lumogen Red F305 dye at concentrations 160, 100 and 75ppm (w/w) equivalent to 113, 71 and 53µg/cm^2.

As excitation source a laser diode with an emission at 450nm laser as light source was used.

The spectrum of the light reaching the solar cells changes deeply as the distance of the aperture from the array increases (Figure 1).

The spectral components of the fluorescence light having wavelength shorter than 630nm are strongly absorbed within the first centimetres of the optical path, resulting useless for this kind of application.

In large area devices, the solar cells will absorb mainly light with wavelength above 630nm and thus, in principle, it is possible to select solar cells having spectral response tailored to operate in that range.

The values of the absorption coefficient in Figure 2 show that the wavelengths outside the absorption spectrum (>620nm) are minimally reduced in the samples with the dye concentration of 100 and 75ppm, above 620nm the losses are caused mainly by surface defects or scattering in the transparent medium.

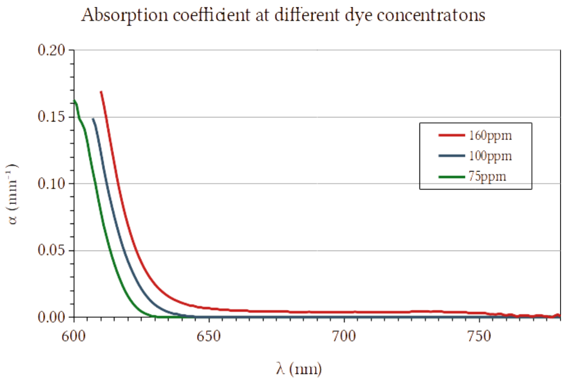


Figure 2: Absorption coefficients of LSCs with different dye concentrations

The 160ppm sample behaves differently with a higher residual absorption up to 750nm.

A more practical quantity that can be obtained by this data is the half-power length which is defined as the distance that light should travel to halve its intensity, this quantity becomes very large (above 2.5m) at 630nm for the sample at 75ppm and above 640nm for the sample at 100ppm.

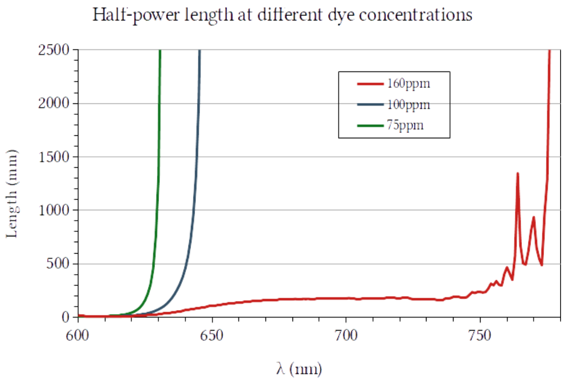


Figure 3: Half-power lengths of LSCs with different dye concentrations

As expected, considering the values of the absorption coefficient, in the 160ppm sample the 2.5m half-power length is reached only at 750nm, this means that the average light path inside the LSC should be kept well below this value and that larger devices require dyes with reduced self-absorption.

Dye concentration can't be increased indefinitely because for higher concentrations the transmittance is reduced without any relevant advantage.

2.2 Prototype configuration

The typical greenhouse hard cover is made of double-wall polycarbonate panels with sizes that range from 1,2x0,6m2 to 3x2m2, this is in contrast with large LSC modules which rarely exceed a short-side length of 50-60cm because the performances of larger devices are limited by self-absorption.

A reasonable trade-off is a module with fixed short side of 50-60cm and variable length of 0.5 to 2m, this size permits to have modules with a large area but where the optical path inside the slab is not so long to limit the performance due to self-absorption.

Polycarbonate covers used in greenhouses ensure high mechanical strength, toughness and impact resistance while the double-wall construction provides good stiffness and a good thermal insulation.

Typically, LSCs are made of PolyMethylMethAcrylate (PMMA) which lacks some of the properties of polycarbonate, in particular, being a more crystalline polymer, it lacks the PC impact resistance and shatters easily.

Moreover, LSC construction requires solid slabs which lack both the stiffness and the thermal insulation properties of double-wall PC.

An option to overcome these problems is the assembly of a double-glazing structure, this approach, while optimal for building integration results in an increase in weight and cost of this construction which are not acceptable for greenhouse panels.

A possible solution to the first problem is the use of an impact resistant PMMA such as Altuglas® ShieldUp, in particular ShieldUp LSCs have been patented [2] jointly by Altuglas and ENI.

Thermal insulation and stiffness have to be obtained differently hence University of Ferrara and ENI are currently working on a patented modular design of LSC for greenhouses which can offer proper rigidity and thermal insulation.

University of Ferrara and Powerglax also developed the photovoltaic cell arrays which have been optimized for large area LSC, these arrays are 25cm long and are composed of 10 monocrystalline silicon solar cells connected in series.

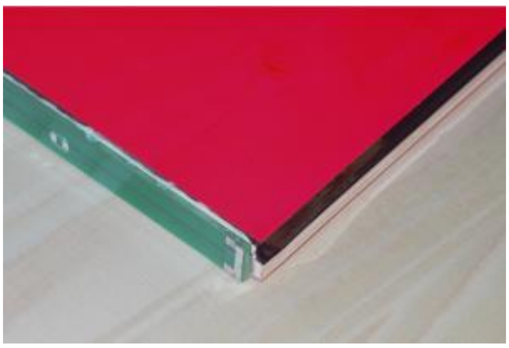


Figure 4: Detail of the prototype edge showing the PV array and the mirror film

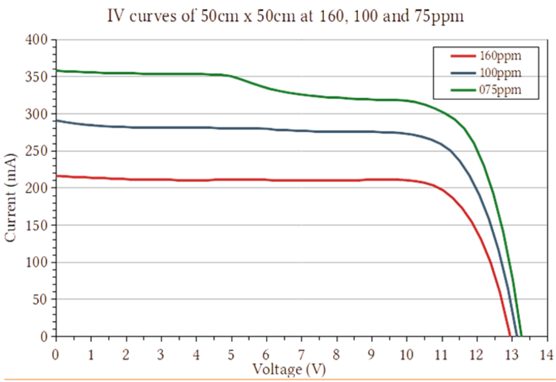
The layout of the solar cells array along the sides has been studied previously and the best design has the PV cells on the two long sides and a mirror on the two short sides, this arrangement ensures a relatively uniform irradiance on the cells along the sides without increasing excessively the light path inside the slab.

The side surfaces not covered by solar cell arrays have been covered with a high efficiency dielectric mirror film (DF2000MA manufactured by 3M). A detail of the side is shown in Figure 4.

2.3 Energy Production

The prototypes were assembled as described in 2.2 and were tested outdoor, in order to obtain the most repeatable results the measurements were taken placing the prototypes on a uniform white background which in turn was placed on a sun tracking system.

The power production from the prototypes hence represents the peak value and in operating conditions (i.e. sun at different angles and plants behind the LSC) are expected to be lower.



Sample	V_{oc} (V)	I_{sc} (mA)	P_{max} (mW)	V_{max} (V)	I_{max} (mA)	FF	GNI (W/m²)	Efficiency
160ppm	12.83	205	2039	10.68	191	0.777	1000	0.85%
100ppm	13.23	284	2806	11.02	255	0.746	1004	1.16%
075ppm	13.13	332	3015	10.93	276	0.692	1021	1.23%

Figure 5: IV curves of the prototypes

Preliminary results show a 1.23 to 0.85% efficiency, that is sufficient to power a ventilation system to reduce the maximum temperature inside the greenhouse or to pump the water used to irrigate the plants.

An interesting result is that the samples with lower dye concentration are performing better than the 160ppm one, this result can be ascribed to the longer half-power length than the sample at 160ppm.

3 PLANTS GROWTH

The green colour of the plants leaves is associated with the presence of chlorophylls (*a* and *b* in most plants) which present two main absorption peaks in the blue (below 500nm) and red (600-800nm) bands and a high reflectivity in the green-yellow (500-600nm) and near infrared (above 800nm) bands.

The Photosynthetically Active Radiation (PAR) is therefore the part of the spectral range capable of activating photosynthesis (400 nm-700 nm) in plants.

Light spectrum hence affects plant growth, if the greenhouse uses LSC devices sunlight is partially absorbed by the dye molecules and at the same time enriched in the emission band of the dye, resulting in a different effect on biomass production and health of the plants.

Plants are particularly sensitive to low levels of blue light and a low red to far red ratio, these situation is typical of the undergrowth of a thick canopy which triggers the shade avoidance response

The typical characters associated to this condition in plants are [3]:

- Lighter leaf colour
- Increased stem length
- Reduced stem diameter
- Reduced dry weight
- Elongation of stem internodes

3.1 PAR attenuation assessment

In literature (Hogewoning et al. (2010) [4] and Lichtenthaler et al. (1980) [5]), it is reported that at least 5-7% of blue light in the spectrum is necessary to ensure plant health.

The PAR attenuation from LSC samples of impact resistant PMMA with different dye concentrations was measured in order to ensure that this condition on the blue light was met.

Samples were 50x50cm² PMMA slabs, 6mm thick with dye concentrations of 75, 100 and 160ppm (45 to 95μg/cm²) and results are shown in Figure 6:

Sample	Transmitted PAR % (400-700nm)	Dye concentration (ppm)	*UV % (300-400nm)*	*Blue % (400-510nm)*	*Green % (510-610nm)*	*Red % (610-720nm)*	*Far-Red % (720-800nm)*
Altuglas ST CS Lumogen F305	40.8	75	2.3	17.6	5.6	46.3	28.2
Altuglas IR SS Lumogen F305	33.2	100	6.1	11.0	2.7	49.9	30.3
Altuglas IR CS Lumogen F305	29.5	160	0.6	7.8	1.8	55.0	34.7

Figure 6: PAR attenuation and transmitted spectrum composition for LSCs with different dye concentrations

The red dye strongly absorbs in the green and yellow bands (500-600nm) and at the same time enriches the spectrum in the red band, the red to far-red ratio is 1.59-1.65 that is a value significantly higher than in natural sunlight which has a ratio close to 1.

Absorption in the blue band is lower than in the green-yellow band and some blue light is available in the transmitted spectrum with a blue to PAR ratio that ranges from 4% to 8% depending on the dye concentration.

Given the PAR measurements and the parameters found in literature all red LSC samples with a dye concentration equal or lower than 160ppm should be able to sustain a heathy plant growth.

3.2 Health parameters

The effects of an insufficient blue illumination or a low red to far-red ratio are well known and therefore is possible to identify some parameters that can be used to rate plant health.

Typical plant health parameters are:

- Stem diameter
- Stem length
- Leaves dry mass
- Roots dry mass
- Dry to fresh weight ratio (whole, leaves, roots)

Another significant parameter (that depends on most of the previous ones) called health index can be defined [6] as:

$$Health\ Index\ (g) = \frac{Stem\ Diameter\ (cm)}{Plant\ Height\ (cm)} \cdot Dry\ Mass\ (\mathrm{g})$$

3.3 Growth results

In parallel to the optical and functional characterization of the LSC functionalized with Lumogen Red F305, Eni carried out an experimental investigation to demonstrate the effect of the light filtered by the LSC on the growth of vegetable species.

Basil seedlings were grown under transparent, red, yellow and orange LSC cubic greenhouses in PMMA with a size of $25x25x25cm^3$, red dye was the Basf Lumogen Red 305 while the other two dyes were orange F500 and yellow DTB/DPA developed by ENI.

A picture of the greenhouses is reported in Figure 7, in addition to LSCs a box made of clear PMMA was taken as reference.

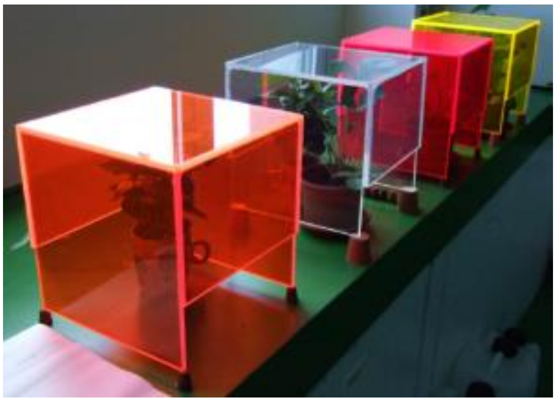


Figure 7: The LSC greenhouse boxes used in this work

The greenhouses with basil seedlings were placed outdoor for 21 days from 17/06 to 11/07 and after this time the health parameters of the seedlings were measured

An automatic irrigation system was used in order to ensure uniform growth conditions

Morphological analysis was carried out to determine the weight (fresh and dry), height and healthy index of the species together with fluorescence measurement to determine the photosynthesis yield of the species grown under LSC.

The performances in terms of growth and photosynthesis yield were compared considering the transparent LSC as a reference (PMMA panel without fluorescent dye).

	Clear	Red (LR305)	Orange (F500)	Yellow (DTB/DPA)
Avg. Stem diameter (mm)	4,3	4.3	3.9	4.1
Stem Height (cm)	26	25	26	25
Leaf Fresh Weight (g)	77.8	85.6	67.9	73.3
Leaf Dry Weight (g)	12.1	11.2	8.9	11.1
Water Content (%)	84.4	86.9	86.9	84.9
Root Dry Weight (g)	112.6	112.7	106.8	86.3
Health Index	**20.8**	**21.1**	**17.2**	**16.1**

Figure 8: Health parameters of the seedling grown in greenhouse LSC boxes

Red LSC cover provides a good vegetative state and a slightly higher healthy index of the species compared to the clear PMMA sample.

Yellow and orange LSCs are not suitable for plants growth, the plants grown under both LSCs show health parameters significantly lower than those grown under red or no LSC.

4 CONCLUSIONS

The experimental activity demonstrated that yellow and orange LSCs are not suitable for plants growth because they absorb most of the blue light.

On the other hand, the red LSC showed good results, providing a good vegetative state and a higher healthy index of the species, without compromising the photosynthesis, this means that a transmitted blue light higher than the critical threshold of 4%, necessary for the photosynthesis process, was achieved for dye concentrations up to 120µg/cm2

This is an interesting result because even the optimal concentration for power production lies in the 50-120µg/cm^2 range.

An additional effect of red LSC filtered illumination is the limitation of Green light component, which is generally not used by the plant, at 6%.

This result is demonstrated with a higher healthy index for basil species grown under red LSC greenhouse, as reported in Figure 8.

Greenhouses are therefore a promising application for LSC devices and LSC systems can provide power to some greenhouse systems like ventilation, irrigation and illumination

4.1 Acknowledgements

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4.2 References

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