Synergistic photon-use in semi-transparent photovoltaic-photosynthesis systems for agrivoltaics

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May 4th 2026
EGU Session SSS9.1
Adaptation and resilience in agriculture: addressing climate change with science and technology

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Outline:

Background:

- Light spectral effects on photosynthesis
- Potential use of semi-transparent photovoltaics (PV) in agrivoltaics
- Luminescent Solar Concentrators (LSCs)

Methods: experimental design and measurement approaches

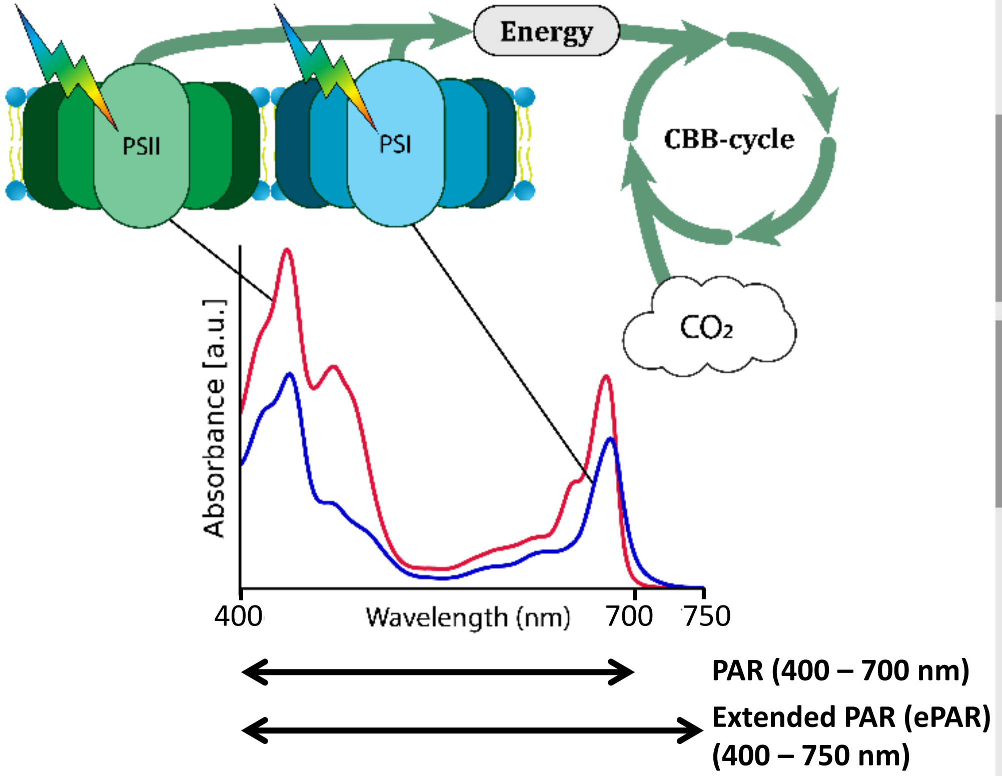
Results:

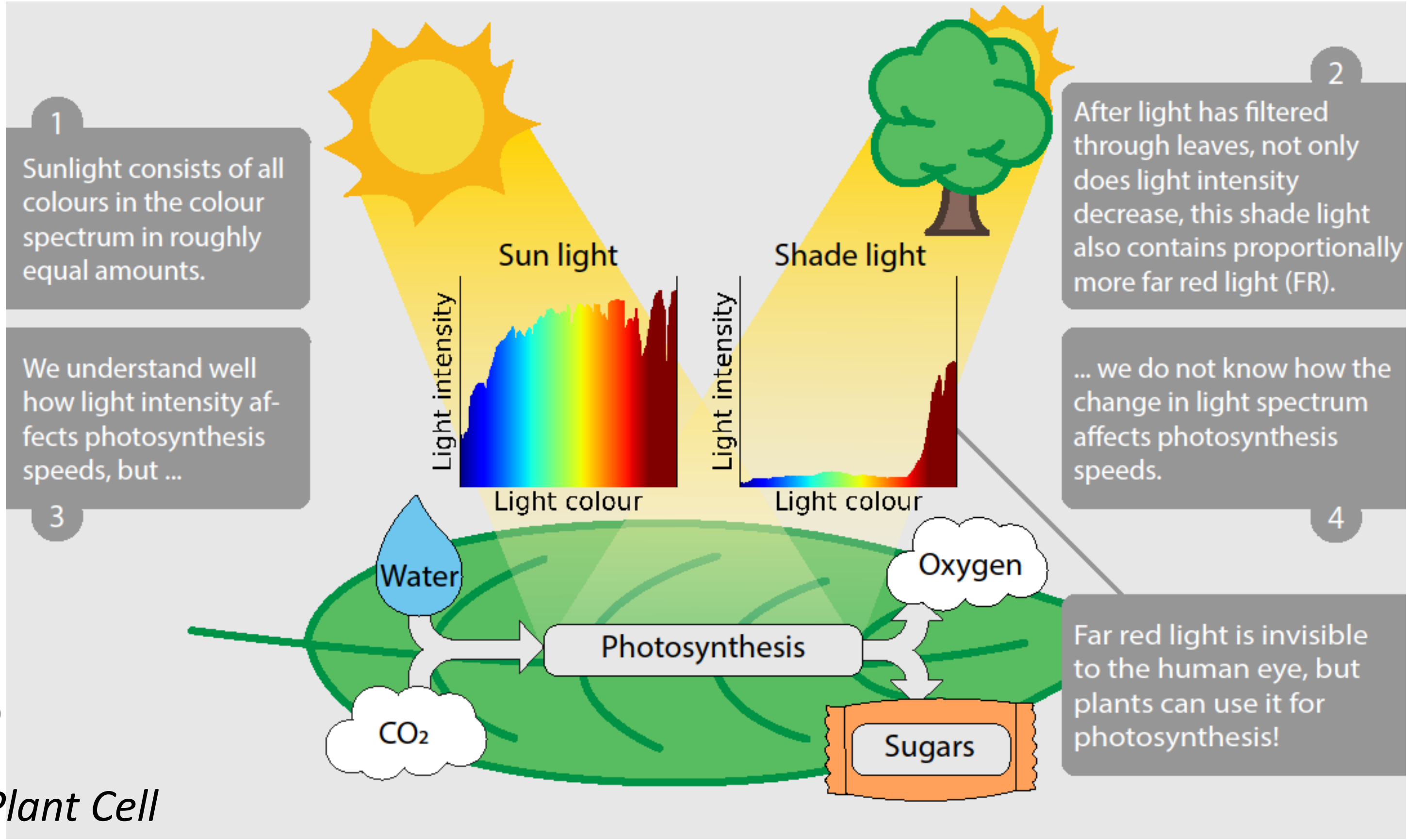
- Electricity generated
- Photosynthesis
- Synergy in electricity generation and photosynthesis

Discussion and outlook: experimental constraints, implications and potential use cases

Background: light spectral effects on photosynthesis

- Plants use monochromatic light of 400 – 700 nm for photosynthesis → Photosynthetic Active Radion (PAR).
- Photo System 1 (PSI) also absorbs light in the 700 – 750 nm range (far-red).
- High far red to PAR ratios naturally occur in lower canopy layers due to spectral filtering by other leaves.
- Recent research: far red light can enhance photosynthesis, when supplemented with light in the PAR range.

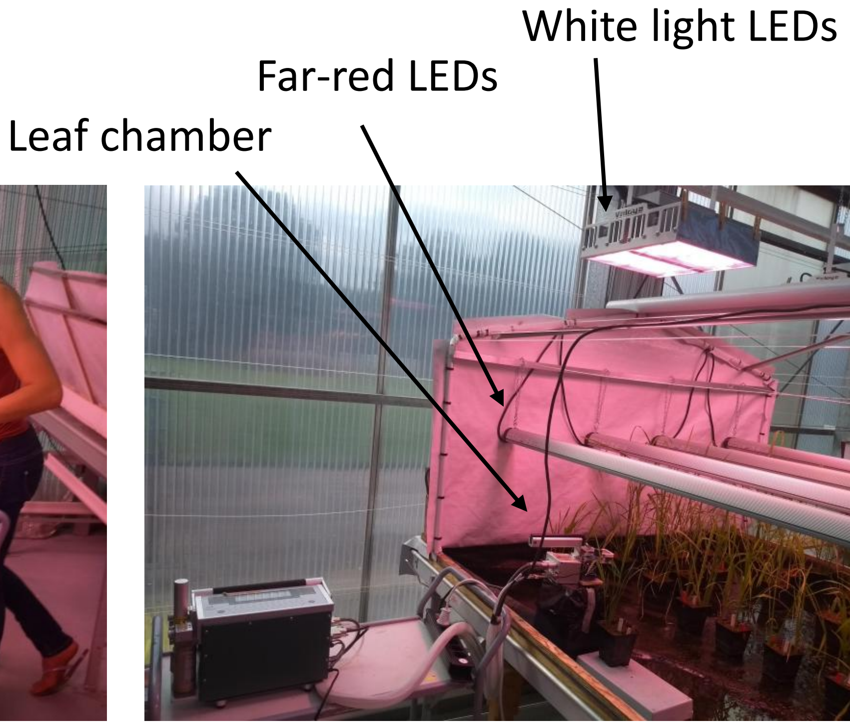


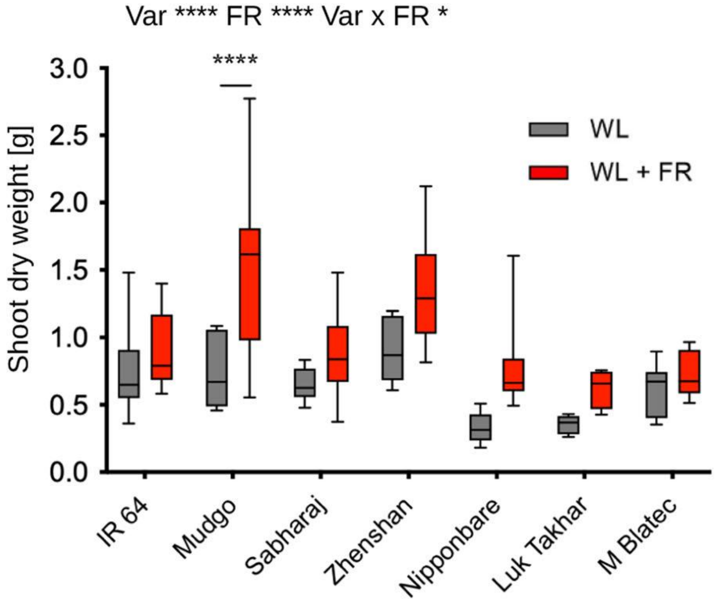


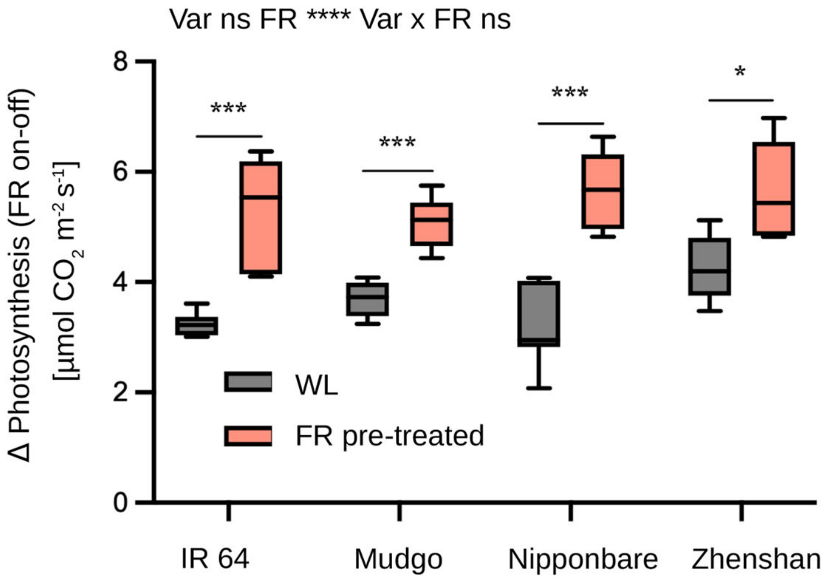
See Jans et al. 2025 *PCE* ; Hogewoning et al. 2012, *The Plant Cell*

Background: light spectral effects on photosynthesis

- Experiment with rice growing in a greenhouse with far-red supplementation as treatment.
- Enhanced dry weight 28 days after sowing with supplemental far red.
- Enhanced photosynthesis with far-red supplementation in all plants, when measured in the experimental setup with clear-top leaf chamber.
- In far-red pre-treated plants, the increase in photosynthesis was larger compared to the control population
- **Light color matters for photosynthesis!**







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See Huber et al. 2023, PCE

Background: agrivoltaics and the potential for semi-transparent PV

- Agrivoltaics combines electricity generation with photovoltaics (PV) and agriculture on the same land.
- Despite potential to optimize the position of solar cells over crops (see Campana et al. 2025), shading imposes a fundamental constraint on biological productivity.
- Semi-transparent solar cells, and specifically wave-length selective solar cells like Luminescent Solar Concentrators (LSCs), hold potential in agrivoltaics to optimize the division of light between plants and PV.

Agrivoltaics

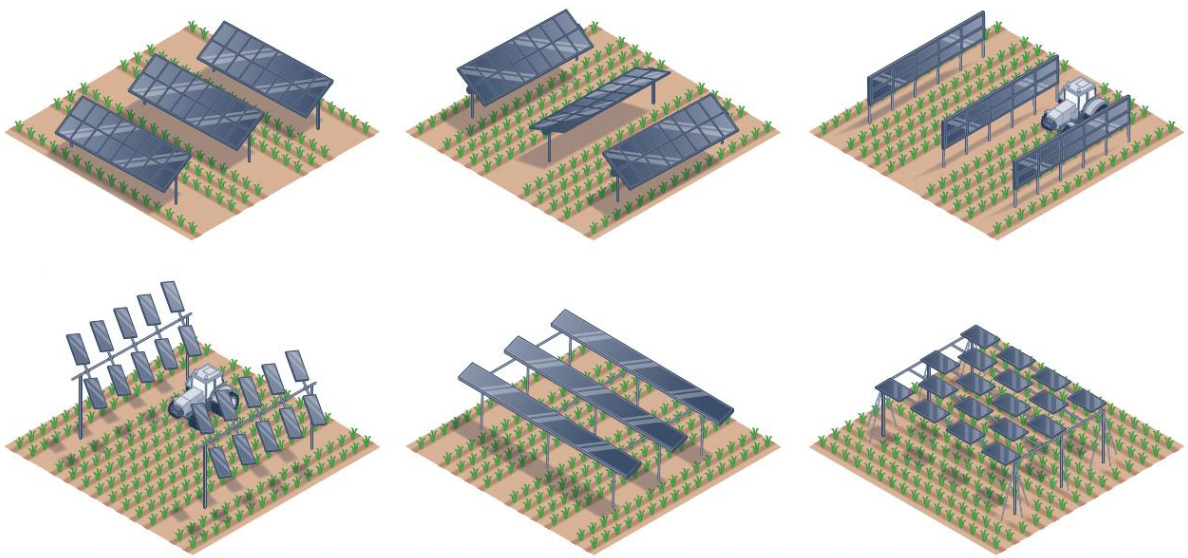
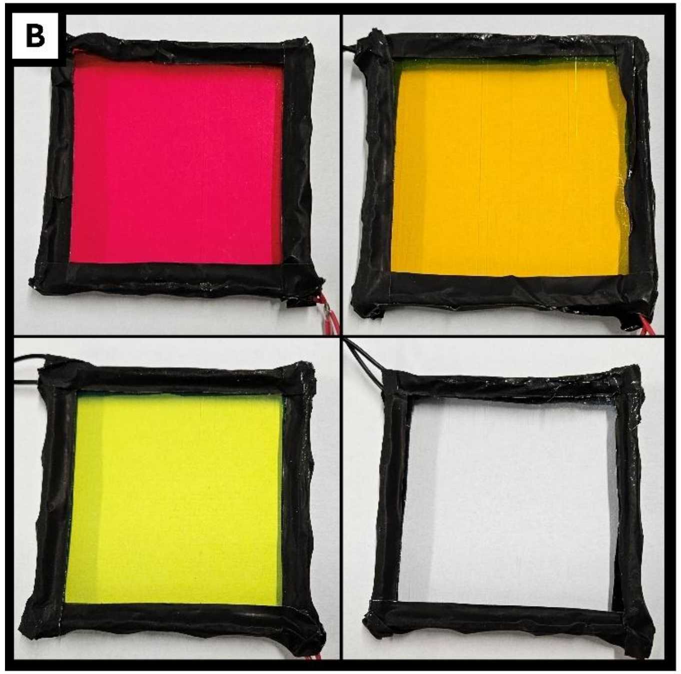


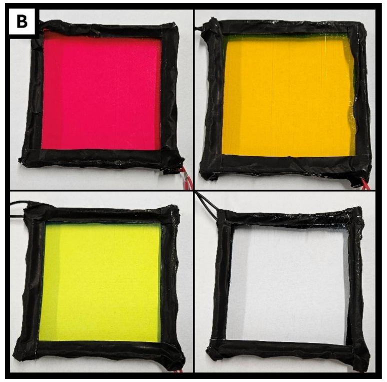
Fig. 1 | Overview of agrivoltaic cropping systems. A, Key areas and topics need to be addressed to improve the competitiveness of agrivoltaic (AV) systems and to tackle current and future challenges. **B**, AV systems configurations: fixed-tilt AV system (part **Ba**), one-axis tracker AV system with Sun-sharing operational strategy (part **Bb**), vertically mounted AV system with bifacial photovoltaic modules (part **Bc**), stilt-mounted overhead two-axis tracker AV system (part **Bd**), lattice overhead AV system (part **Be**) and tensile overhead chessboard AV system (part **Bf**).

Campana et al. 2025, Nature Reviews Clean Technology

Luminescent Solar Concentrators (LSCs)



Background: Luminescent Solar Concentrators (LSCs)



How does an LSC work?

Light comes in from above and:

i. a photon is absorbed by the dye inside the LSC and emitted at a larger wave length. If emitted at higher than critical angle, the photon is guided by total internal reflection to the LSC edge and captured by the solar cell;

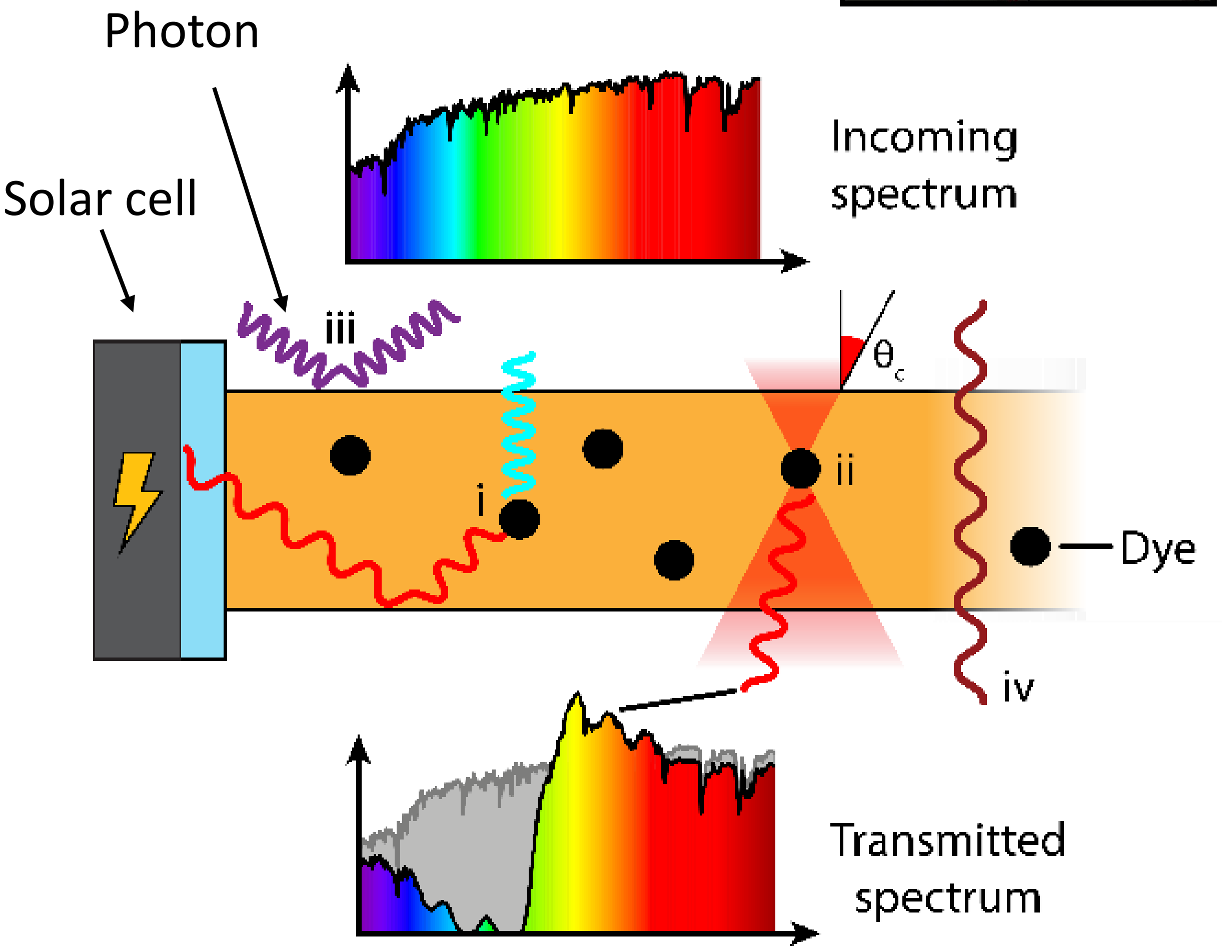
ii. if the photon is emitted at lower than critical angle, the photon exits the LSC through the top or bottom;

iii. photons can reflect from the top of the LSC;

iv. photons can pass through the LSC with;

The transmitted spectrum is a combination of the incoming spectrum and the spectral characteristics of the LSC.

LSC side view



Research question and aims:

Background:
There is a clear potential for the use of semi-transparent PV in agrivoltaics. Specifically, wavelength-selective PV (like LSC-technology) is promising as spectral characteristics can be optimized to specific use cases, light environments and plant species.

Research question:
Which spectral characteristics offers the most productive combination of light capture for electricity generation and light transmission for photosynthesis?

Aims:
Develop an experimental framework to quantify the combination of photosynthesis and electricity generation using wave-length selective PV underneath the same light source.

Methods: experimental design

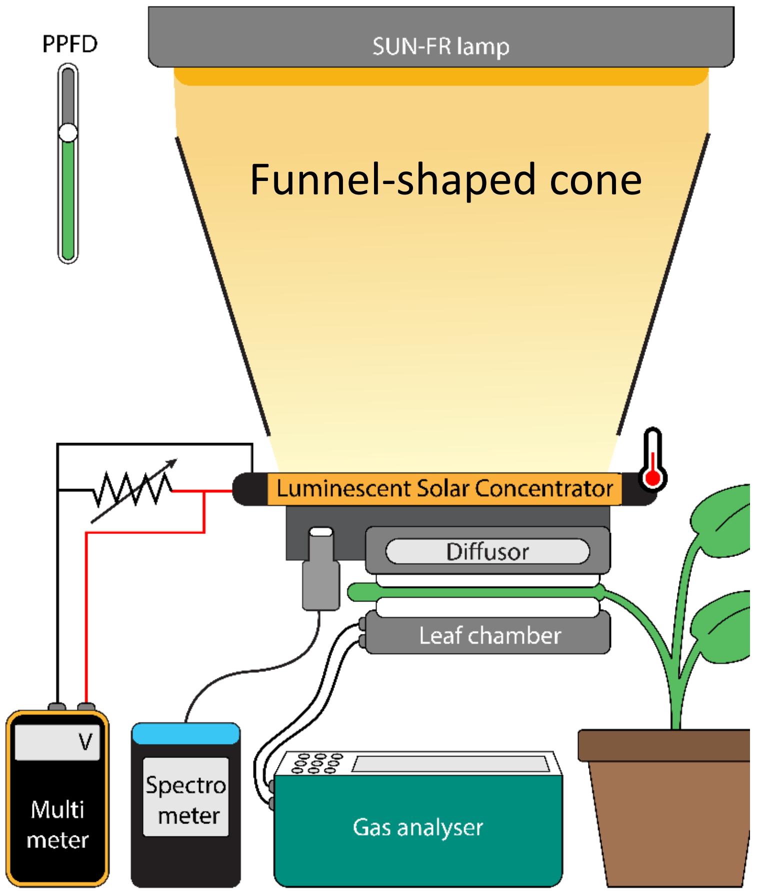
Integrated experimental setup (top to bottom):

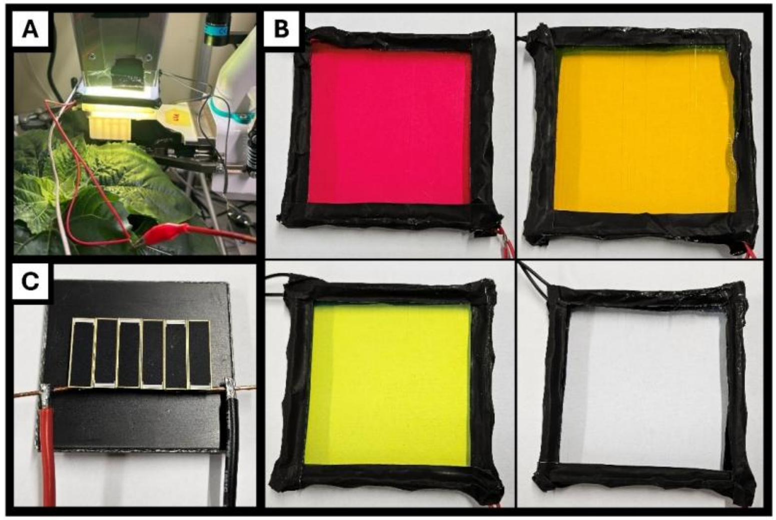
- SUN-FR lamp that emits a near-realistic sunlight spectrum in the PAR and far-red range (400 – 750 nm) (Wassenaar et al. 2026, *under review*)
- Funnel-shaped cone to direct the light onto the LSC and leaf
- Placeholder to mount different LSCs and reference (non-transparent) solar cells
- Diffusor to limit light scattering to influence the results
- Leaf chamber with transparent top for photosynthesis measurements

Plants: High-light tolerant sunflower and shade-tolerant Calathea

Solar cells:

- Four 70x70 mm^2 LSCs (Röhm GmbH) in the colors red, orange, green and blank (without dye)
- Each LSC has four silicon PV cells (IXYS KXOB22-12X1F) mounted on the sides
- One reference (non-transparent) solar cell was constructed using the six of the same cells, but then facing upwards





Methods: experimental design

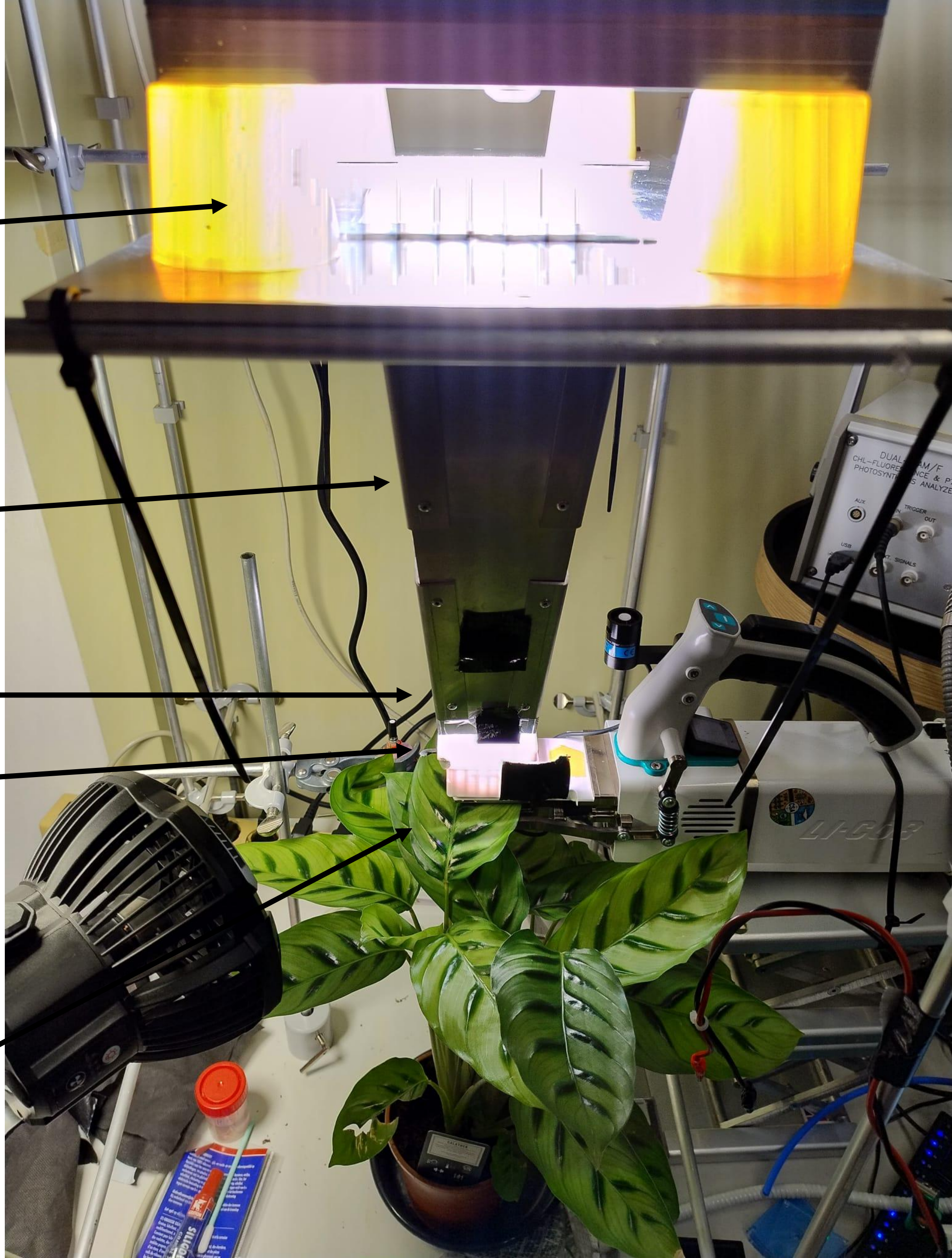
SUN-FR lamp

Funnel-shaped cone

Placeholder for PV cells

Diffusor

Leaf chamber

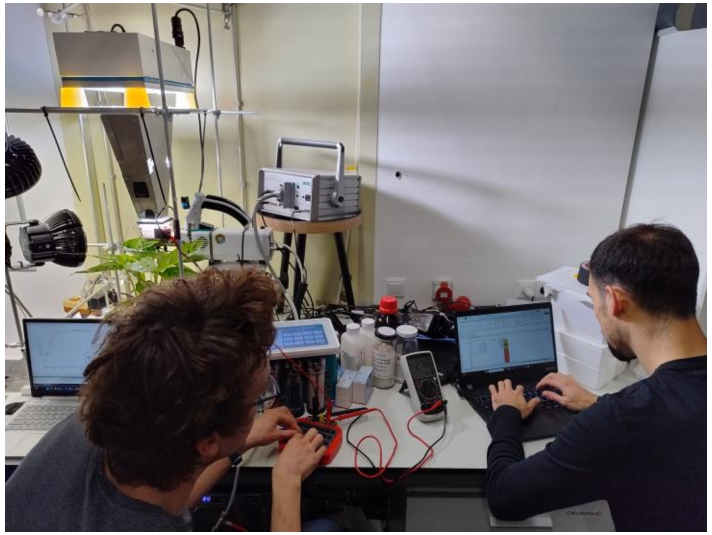


Methods: experimental design

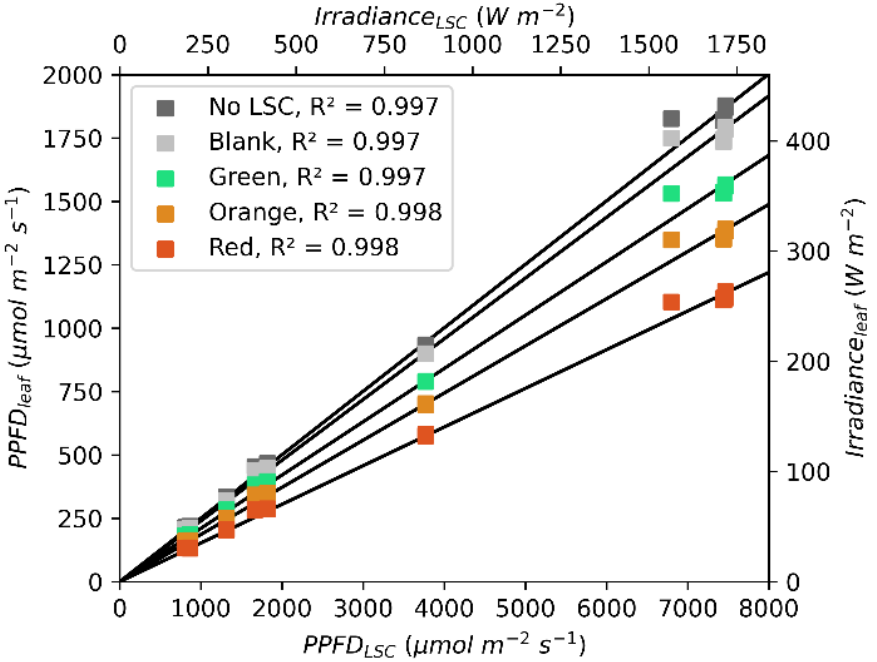
Measurements conducted:

- Current-voltage curves of the solar cells were measured using multi-meter and a variables resistor and temperature corrected.
- Light intensities and spectra were measured at the locations of the solar cell and leaf using a spectrometer.
- Photosynthesis was measured using a Li-Cor LI-6800 portable photosynthesis system with IRGA gas analyzers.
- Light settings adjusted to represent '**low light**', '**medium light**', and '**high light**' intensities at the leaf, reflecting species-specific light responses.
- Ligh intensities at the leaf ranged from approximately 100 tot 2000 µmol/m^2/s to cover the range from light limitation to light saturation.
- Light intensity at the LSC ranged from approximately 600 tot 7500 µmol/m^2/s, which is approximately similar to 1712 W/m² for the incident light spectrum (nearly double typical maximum sunlight).
- All measurements were replicated three times on different plans.

Ongoing measurements



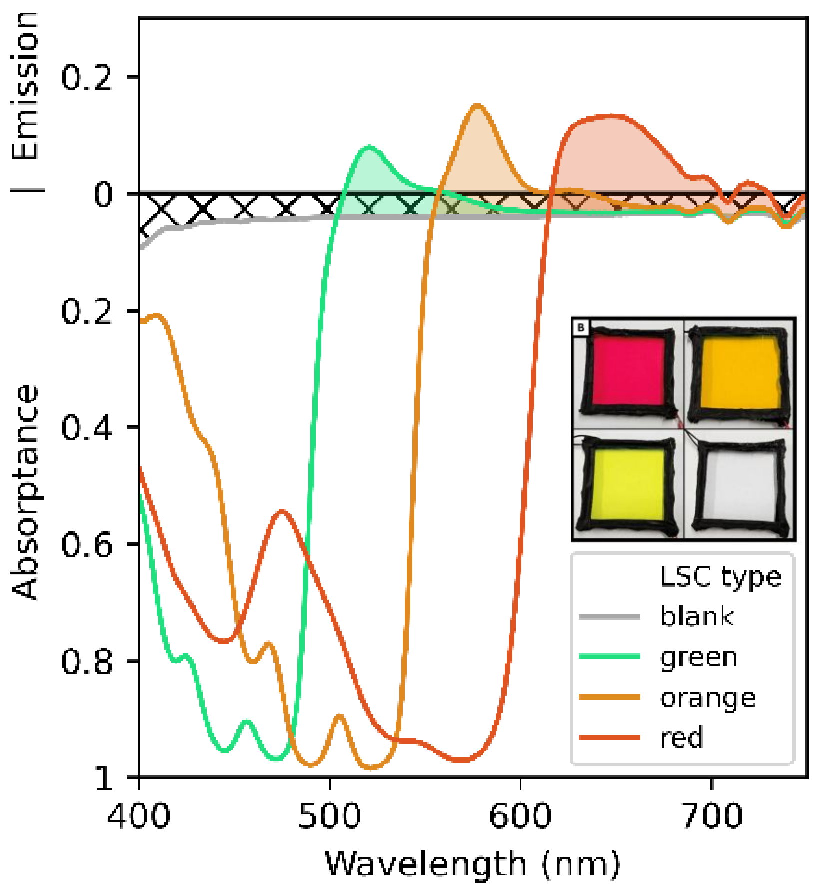
Experimental light conditions



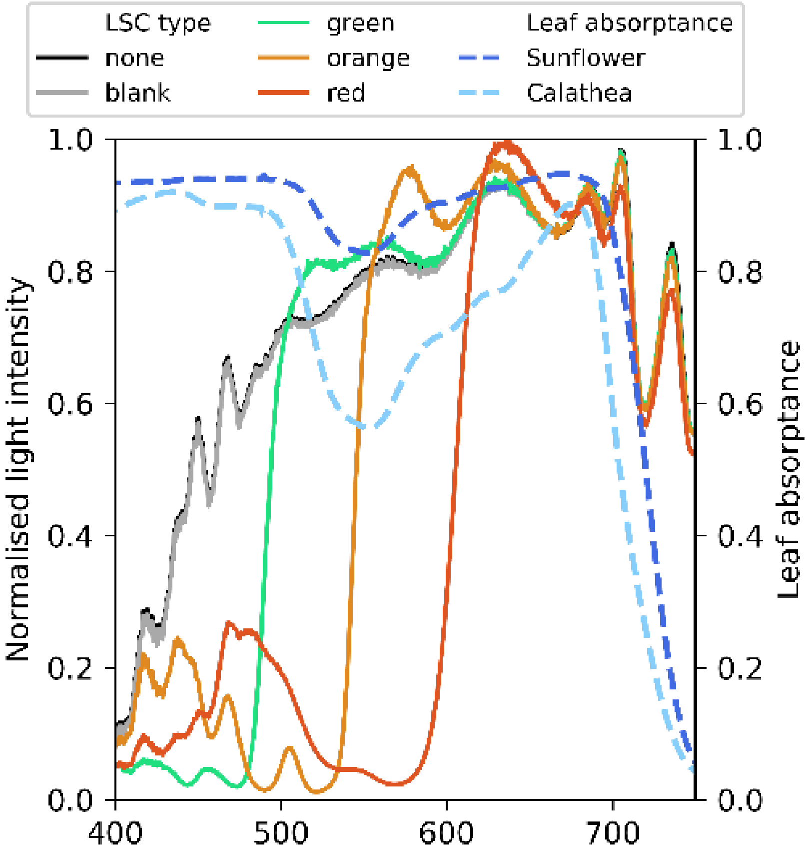
Results: LSC light transmission and leaf absorptance

- The four LSCs show clear differences in absorptance and emission spectra.
- The blank LSC (without dye) shows the effect of light scattering from the top of the LSC.
- Different absorptance spectra for sunflower and Calathea.

LSC spectral characteristics

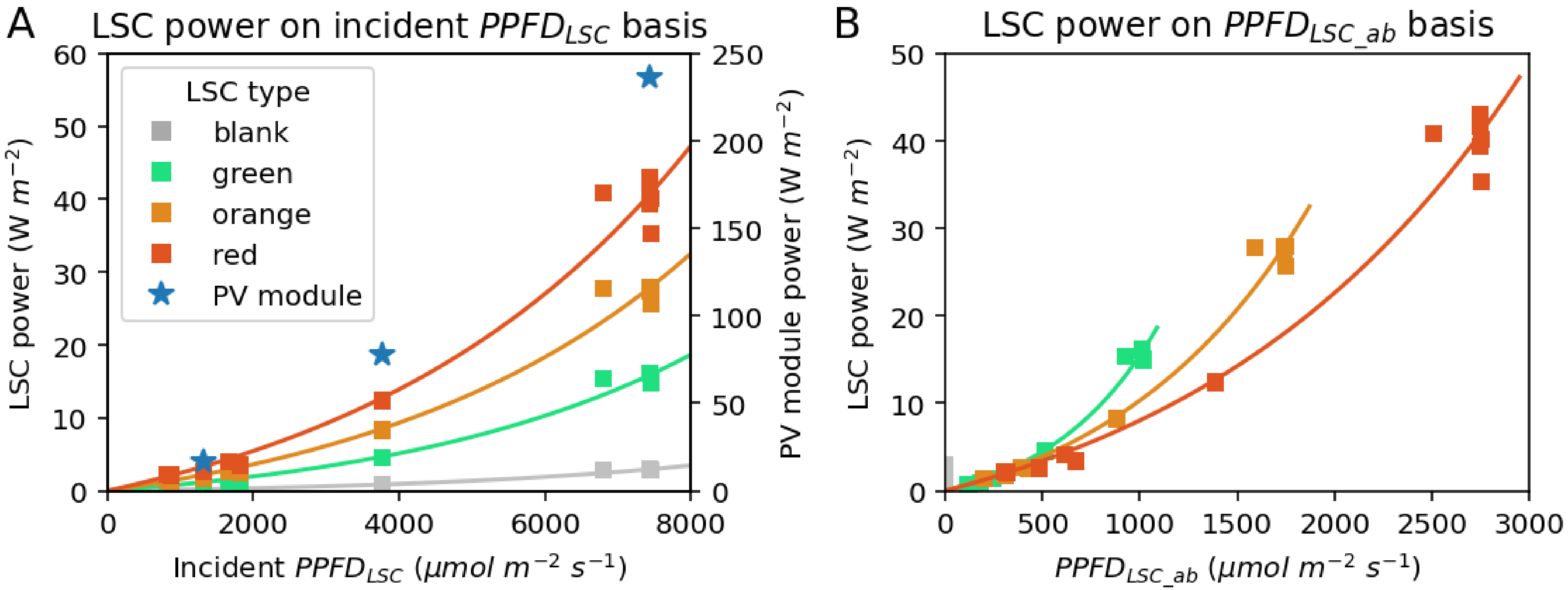


Leaf level light intensity and absorption



Results: electricity generation

- LSC power output increases with higher incident light intensity.
- Least transparent LSCs, measured as the amount of photosynthetically active photons absorbed by the LSC ($PPFD_{LSC\_ab}$), have highest power output.
- For a given $PPFD_{LSC\_ab}$, LSC power output decreased with increasing transparency.



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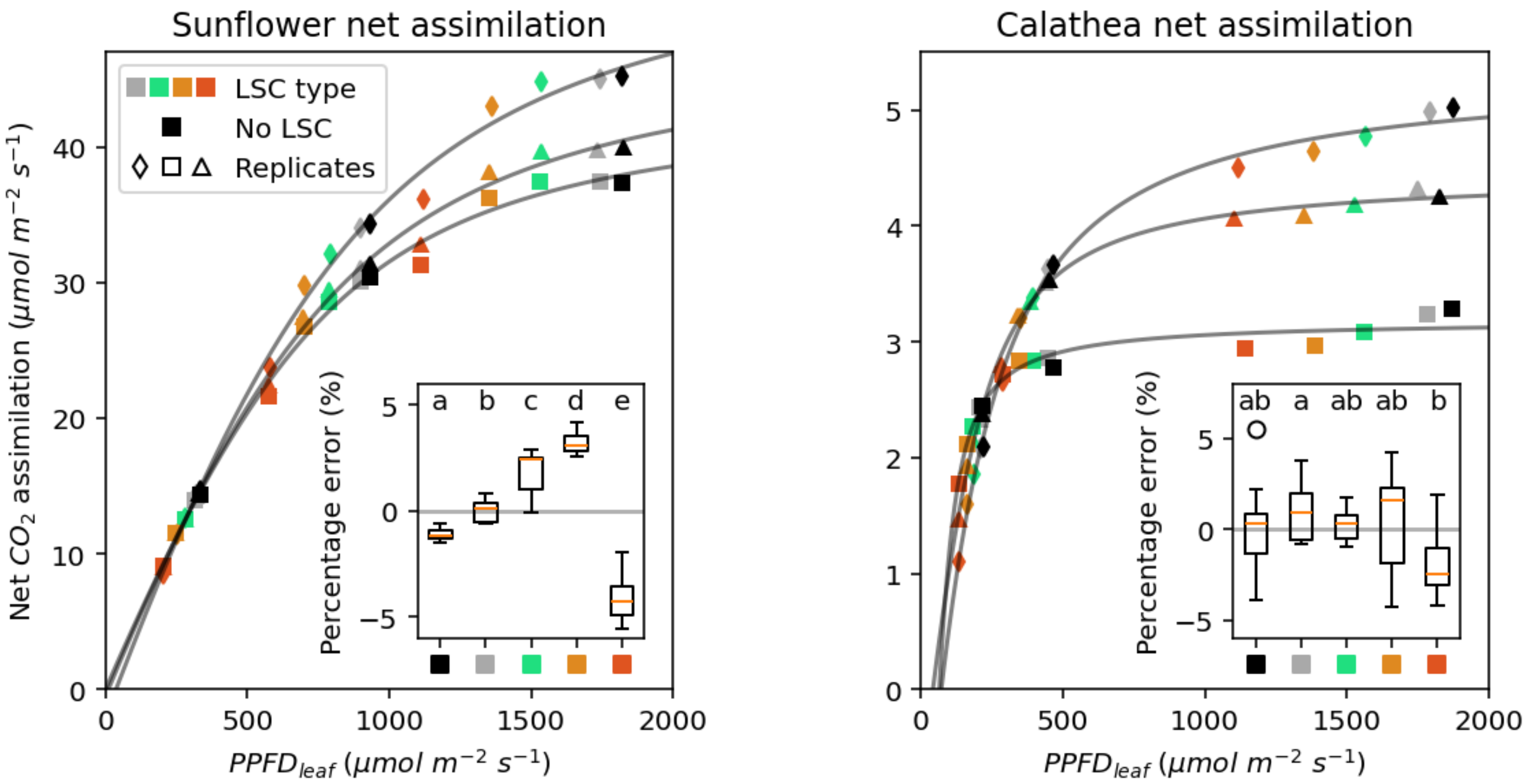
Results: photosynthesis

- Both species reveal the well-know hyperbolic light saturation curve.
- Sunflower saturates at much higher light intensities, and reaches higher photosynthetic CO2 assimilation, compared to Calathea.
- In sunflower, we observed significant differences in photosynthesis rates for a given light intensity, with highest relative rates underneath the orange and green LSCs.



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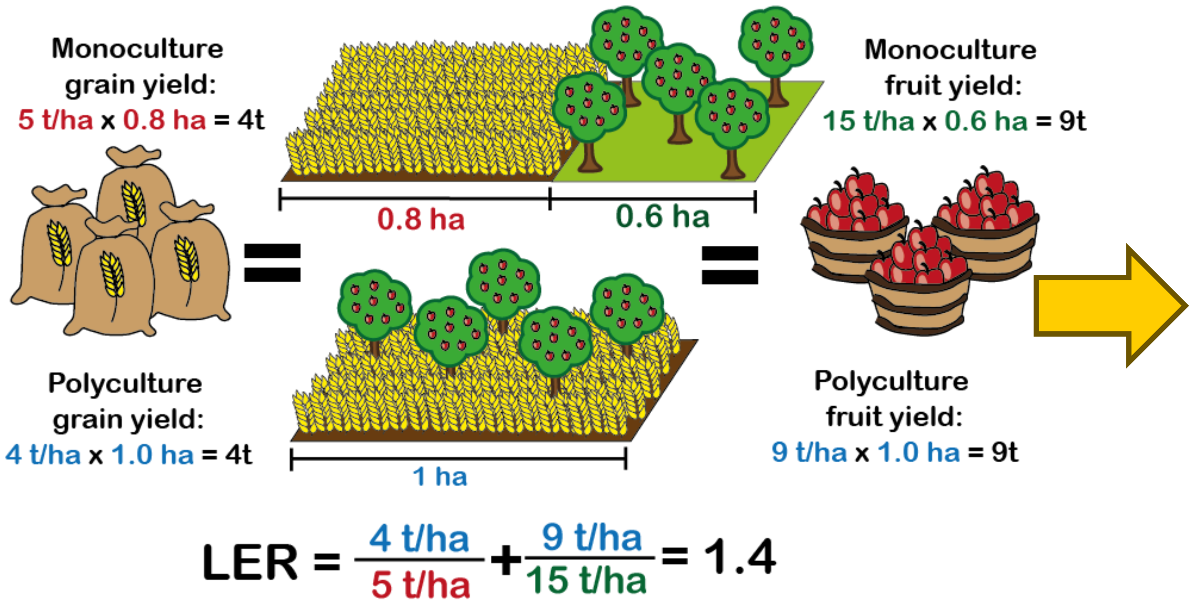
Results: combined electricity generation and photosynthesis

How to quantify the combined electricity-photosynthesis output?

We applied the concept of the Land Equivalent Ratio (LER) to leaves positioned under semi-transparent PV as the Photon-use Equivalent Ratio (PER):



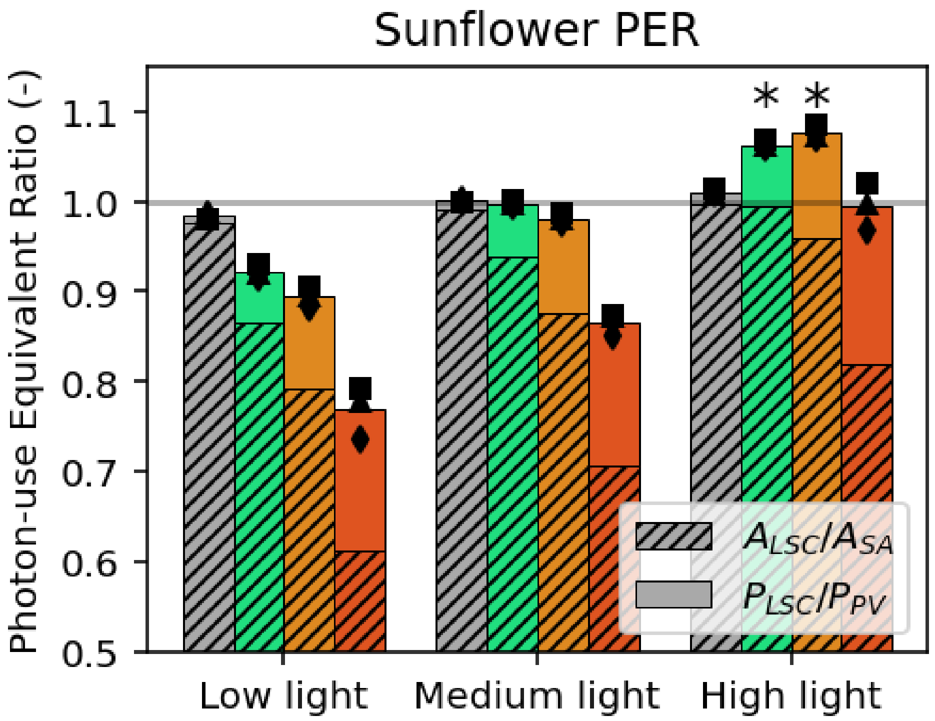
$$PER = \frac{P_{LSC}}{P_{PV}} + \frac{A_{LSC}}{A_{SA}}$$

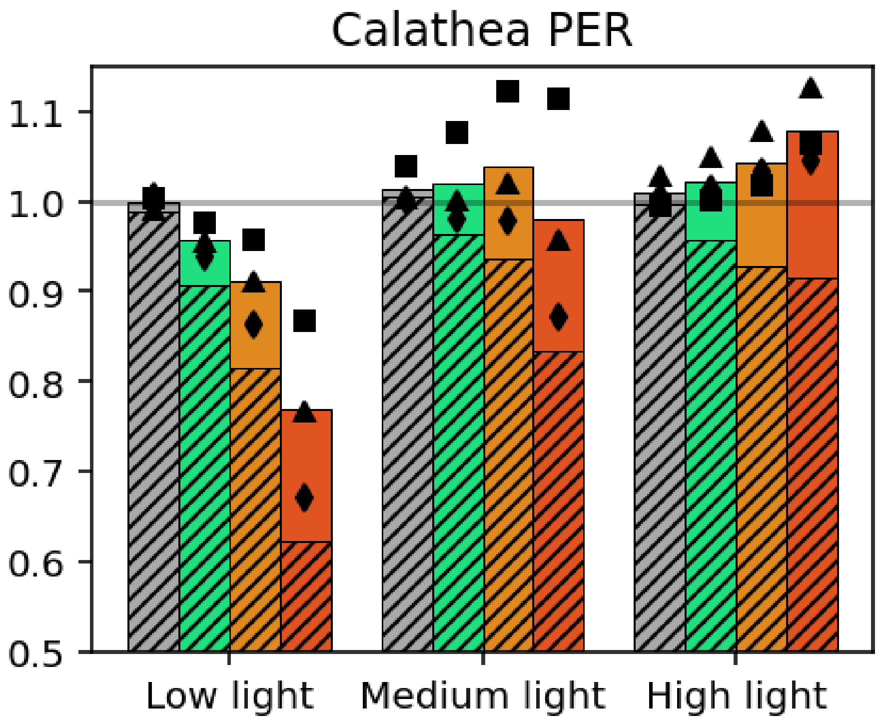
PER: Photon-use Equivalent Ratio (-)
P_{LSC} : power generated by the LSC (W/m^2)
P_{PV} : power generated the non-transparent PV cell (W/m^2)
A_{LSC} : Photosynthesis underneath the LSC (μmol/m^2/s)
A_{SA} : Photosynthesis of a stand-alone leaf (μmol/m^2/s)

Image by Tobi Kellner: https://en.wikipedia.org/wiki/File:Land_Equivalent_Ratio_v2_0_complex.png

Results: combined electricity generation and photosynthesis

- Using the PER metric revels considerable differences in combined productivity between device-species combinations.
- No consistent responses to LSC color were observed (significant interaction effect between light intensity and LSC color for both species).
- PERs > 1 were observed in sunflower underneath the green and orange LSC, highlighting synergistic photon use, compared to stand-alone leaves and non-transparent solar cells.





Sunflower stats:

* One-sided T-Test: $p < 0.05$

2-way ANOVA

- LSC-type: $p < 0.001$
- Light intensity: $p < 0.001$
- Interaction: $p < 0.001$

Calathea stats:

2-way ANOVA

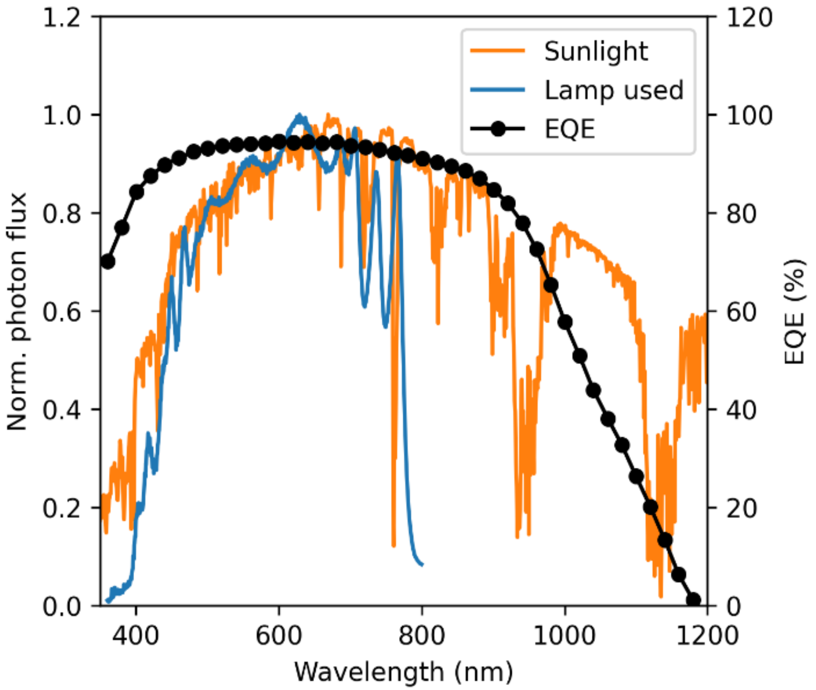
- LSC-type: $p < 0.001$
- Light intensity: $p = 0.07$
- Interaction: $p < 0.001$

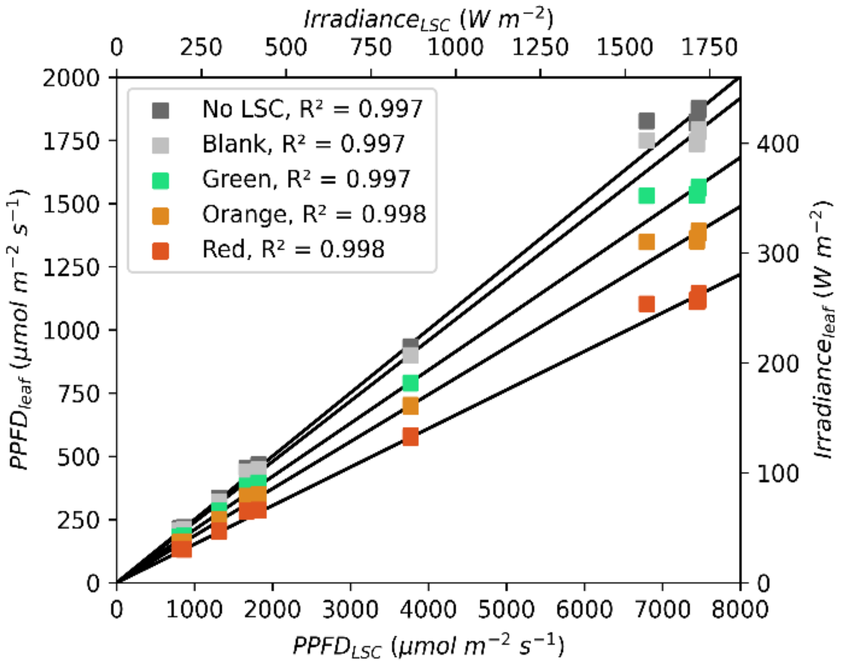
Discussion: experimental constraints

- Although the SUN-FR light source reproduces the sunlight spectrum in the PAR and far-red range very well, it does not emit photons in longer wave lengths.

- Experimental light intensity at the LSC was nearly double that of natural sunlight in the highest light conditions to compensate for light dissipation along the light path.

- Further testing needed to see if results transfer to canopies and full spectrum sunlight.





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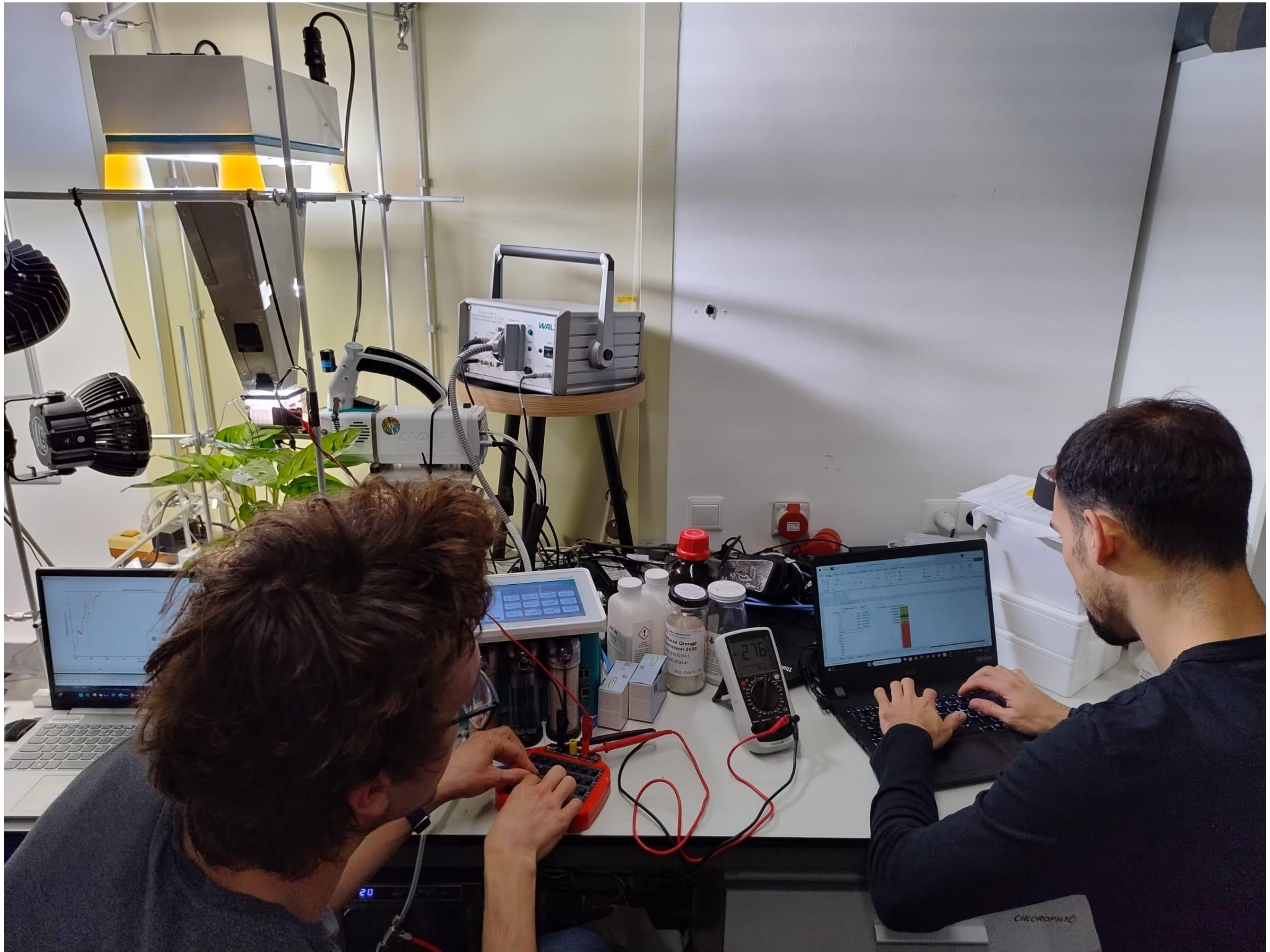
Discussion: implications and potential use cases

- Experimental setup allows for relatively quick screening of LSC devices and plant species.
- The PER metric provides a standardizable approach to compare combined electricity-photosynthesis output across device-species combinations and experimental setups.
- Our results with PER > 1 highlight that some combinations of light intensity, LSC color and plant species, achieve synergistic photon use compared to stand-alone PV and leaves.
- Potentially useful for greenhouse horticulture and field-based agrivoltaics, specifically in environments with high ambient light (instead of using light-blocking screens).
- Little knowledge on the light spectral effects on plant functioning and photosynthesis.

A big thank you to Tinko Jans and Raimon Terricabres-Polo!



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- Maarten L.J. Wassenaar, Pieke Weerd, van der, Steven M Driever, Leo F.M. Marcelis, Douglas J. Lynch, Ian R.A. Sillie, and Wim Van Ieperen. Far-red light enhances mesophyll conductance and photosynthesis in tomato – but only at fractions lower than the natural far-red fraction in sunlight (under review)

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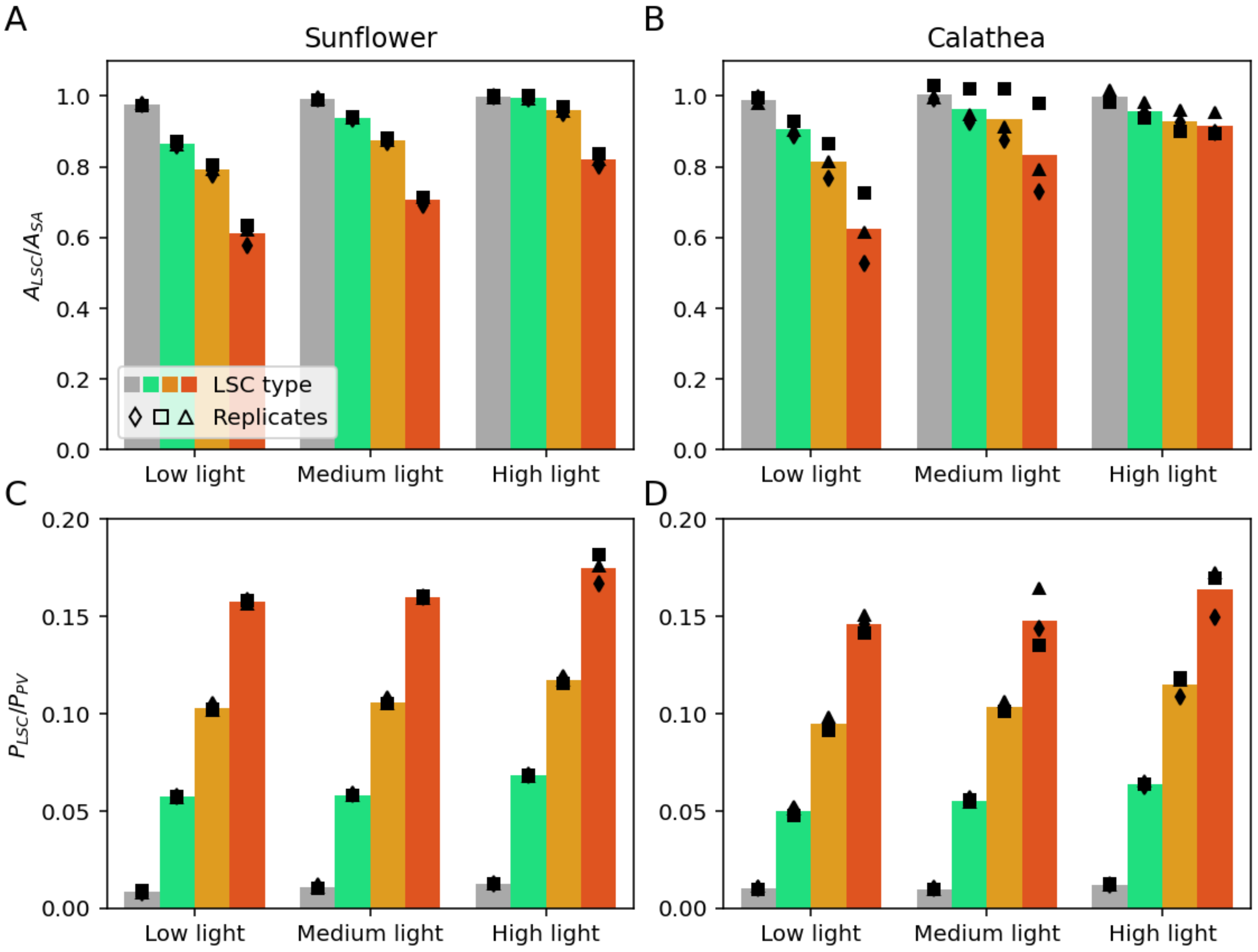
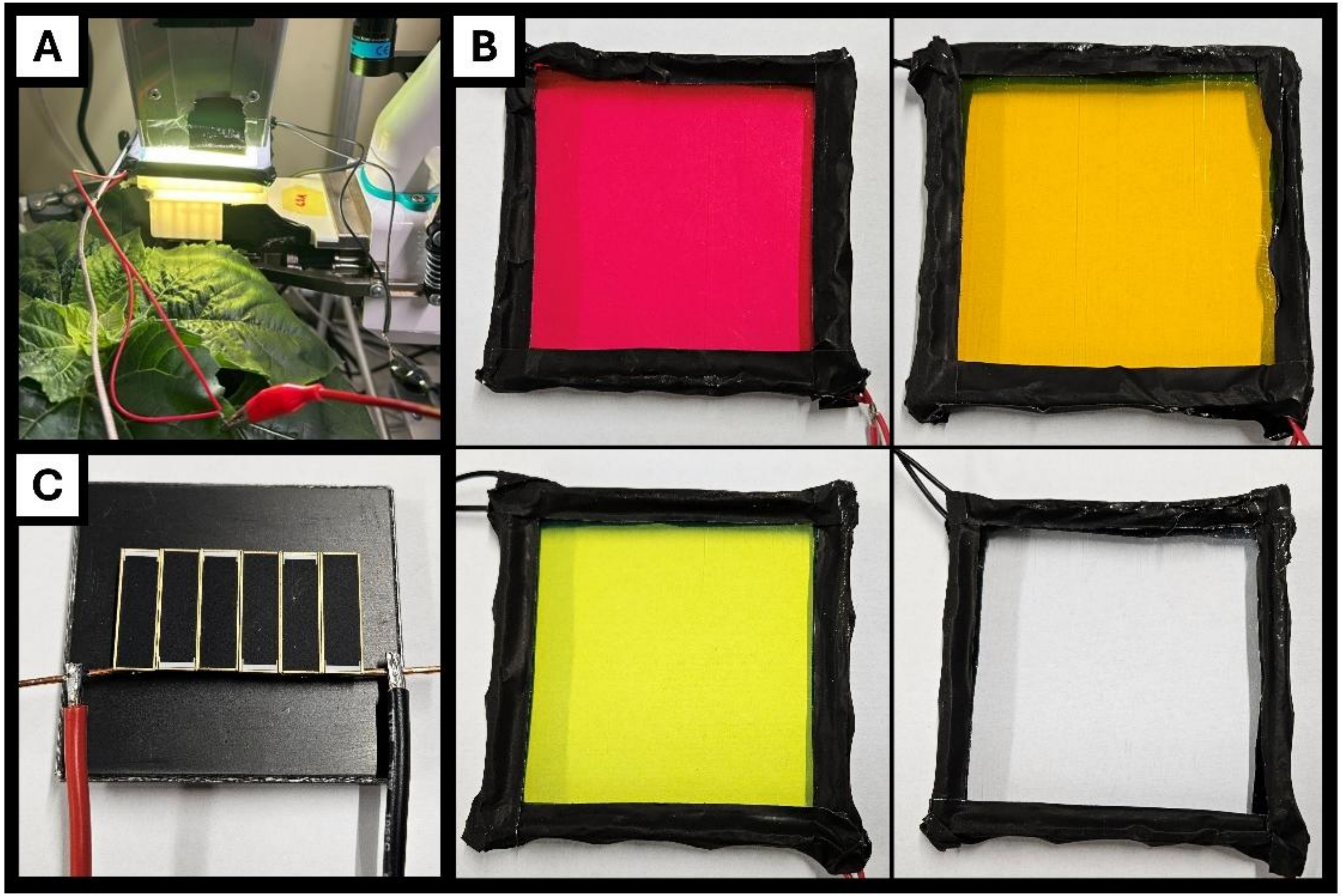
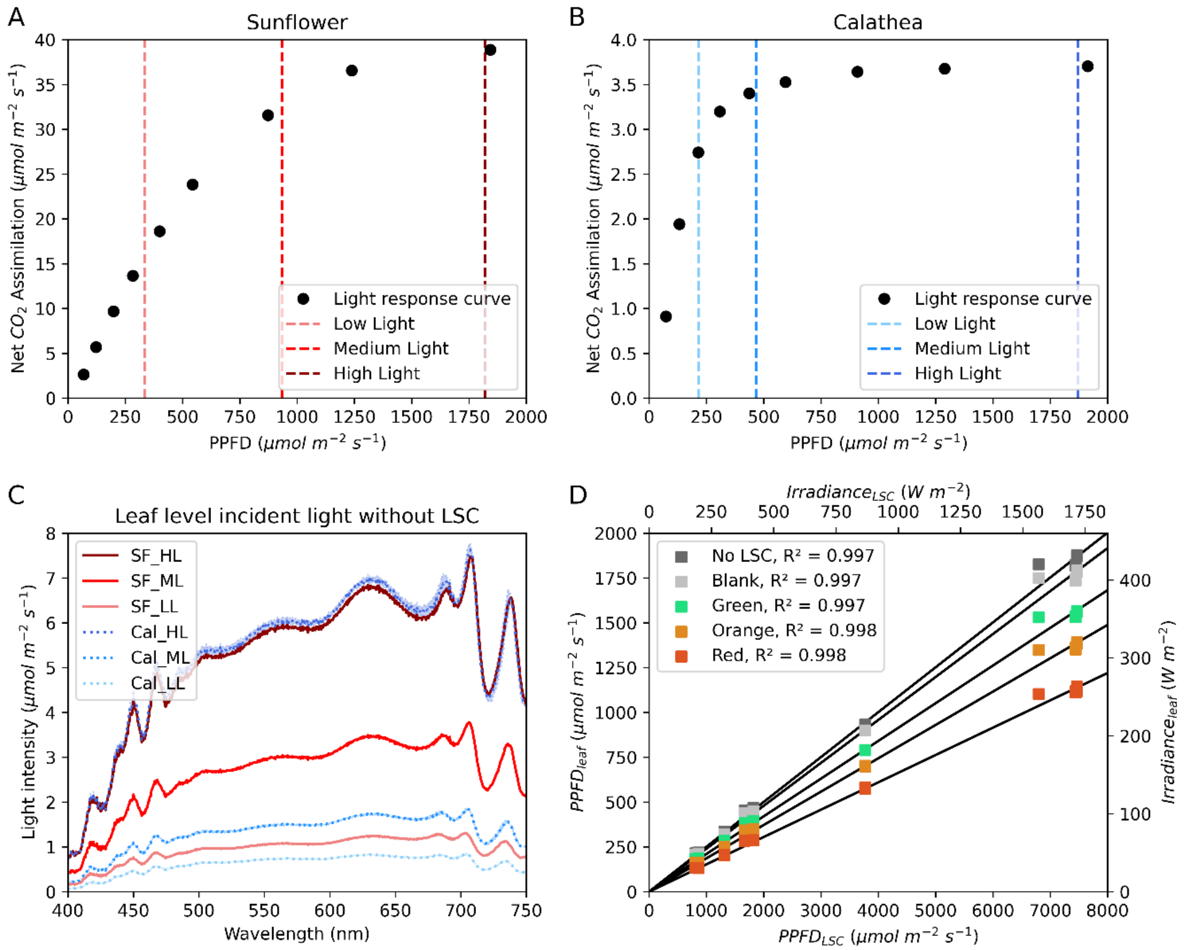


Measurement	Plant species	Light intensity	LSC type	Interaction
Equivalent photosynthesis (A_{LSC} / A_{SA})	Sunflower	<0.001	<0.001	<0.001
Equivalent photosynthesis (A_{LSC} / A_{SA})	Calathea	<0.001	<0.001	0.002
Equivalent LSC power (P_{LSC} / P_{PV})	Sunflower	<0.001	<0.001	<0.001
Equivalent LSC power (P_{LSC} / P_{PV}.	Calathea	<0.001	<0.001	0.049

Equivalent photon use by photosynthesis (A_{LSC} / A_{SA}) for **(A)** Sunflower and **(B)** Calathea. Equivalent photon use by LSC (P_{LSC} / P_{PV}) for **(C)** Sunflower and **(D)** Calathea. Barplots are coloured according to LSC type, individual replicates are plotted as single markers (n=3 per bar). Table shows 2-way ANOVA statistics.



Experimental setup and photovoltaic modules. **(A)** Light concentrating cone projecting light onto a Luminescent Solar Concentrator (LSC) positioned above the leaf chamber with enclosed leaf. **(B)** The four LSCs used in this study consisting of 6 mm thick 70x70 mm^2 acrylic sheets from Röhm GmbH of the types (from top left to bottom right): Red (3C22 GT), Orange (201 GT), Green (6C02 GT), and a blank with no dye (0A000 GT). **(C)** Reference non-transparent PV module consisting of six monocrystalline silicon PV cells (IXYS KXOB22-12X1F), the same type as mounted on the sides of the LSCs.



Experimental light conditions. Light intensities at leaf level were determined based on light response curves of **(A)** high-light tolerant sunflower (*Helianthus annuus*) and **(B)** shade tolerant Calathea (*Calathea leopardina*). Light intensities were controlled using custom control software and measured at the LSC position and within the leaf chamber at the leaf position using a spectrometer (ST-VIS, Ocean Optics) with an optical fibre centred in the light beam. Incident light intensities were set in absence of an LSC at three intensities ranging from photosynthetic light limitation (termed *low light*), through intermediate intensity (termed *medium light*), up to photosynthetic light saturation (termed *high light*), as indicated by the vertical dashed lines. The low light conditions for both species were set at the initial linear part of their light response curves and the medium light conditions captures the early transition towards light saturation. Light intensity was expressed as Photosynthetic Photon Flux Density (PPFD) integrated across 400 – 750 nm to include all (potential) photosynthetically active wavelengths. **(C)** Incident light spectra at leaf level in absence of an LSC for Sunflower (SF) and Calathea (Cal) at high light (HL), medium light (ML), and low light (LL). **(D)** Experimental light conditions expressed as PPFD at the position of the LSC ($PPFD_{LSC}$) and at the position of the leaf ($PPFD_{leaf}$). Light intensities at LSC level were also expressed as irradiance ($Irradience_{LSC}$) in the typical unit W m^{-2} by integrating the photon flux over the incident light spectra. Note that, in order to achieve photosynthetic light saturation at leaf level in our high light experimental conditions, $PPFD_{LSC}$ reached 7445 µmol m^{-2} s^{-1}, equivalent to irradiance of 1712 W m^{-2} when integrated across the incident light spectrum, nearly twice typical midday clear-sky conditions.

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