PaCMan Light Engines
Re-Lamping for Lighting Optimitization

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Introduction
About us

MEG stand for Mutable Efficient Growing.

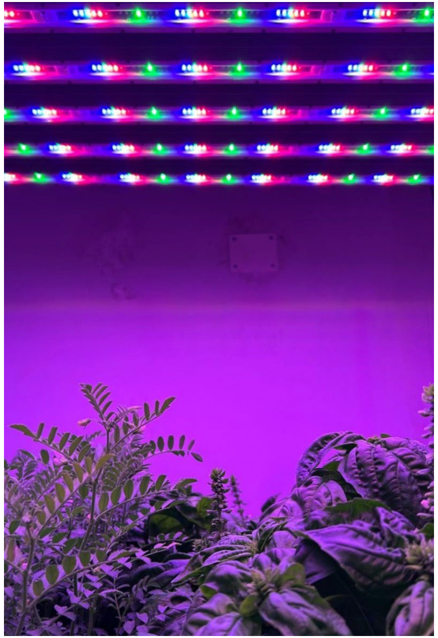
We are a consultancy firm that operates in the fields of applied photobiology for bio+agro-industry, serving as a link between laboratory research and feasibility-oriented industrial application.

20 years of experience with solid-state lighting (LED) and related technologies has led MEG to become a technology partner for **leading-edge advancements.**

Our aim is to be part of R&D&I oriented networks, to better expand and share our knowledge.

Current areas of work

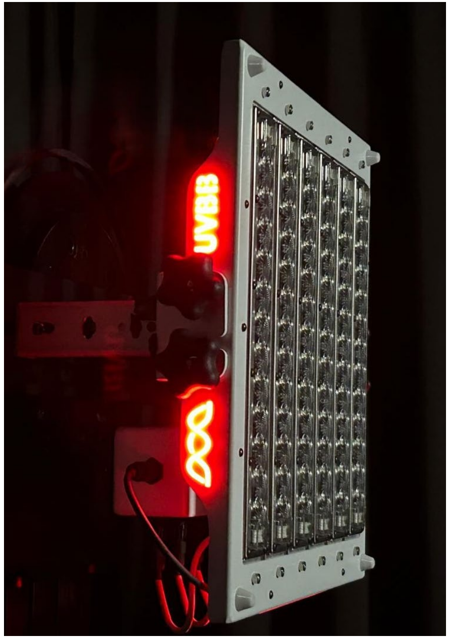
Our practice applied



Higher plants

Microalgae

Insects



UVBB

Introduction
About this presentation

PACMaN represents a breakthrough in controlled-environment agriculture research facilities.

Our mission: transform lighting from a passive component into an active driver of biological performance.

This presentation outlines MEG Science's approach to re-lamping for lighting optimization, combining engineering, simulation, and applied research.

Experimental cultivation being carried out in PaCMaN.

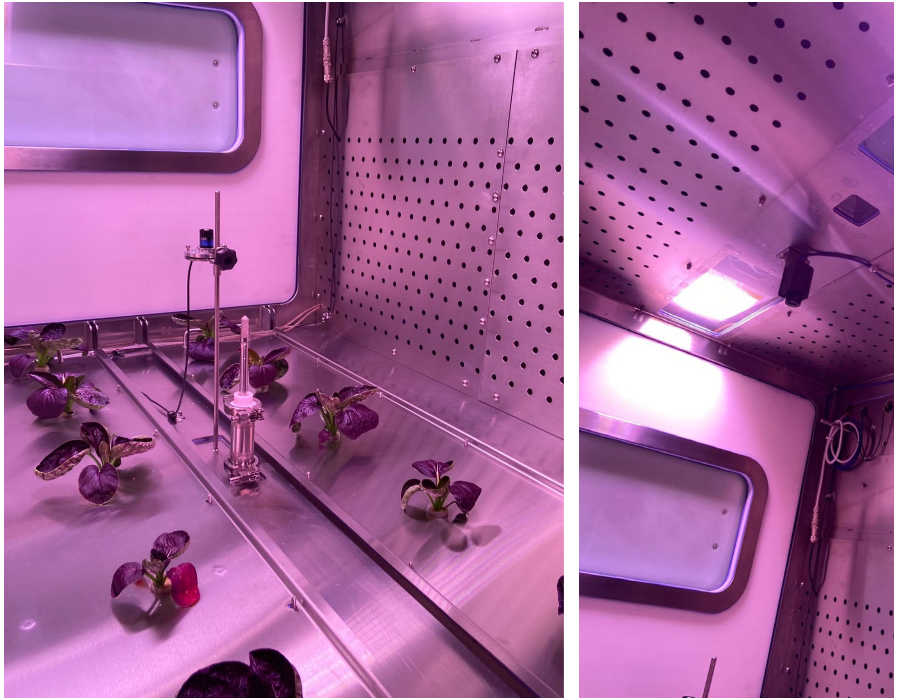
Initial PaCMaN State of the Art

Limitations in Uniformity, Spectrum, and Integration

The original PaCMaN setup faced critical limitations. Light distribution lacked uniformity, creating inconsistent growth conditions.

The system relied on forced integration of commercial lamps, treating light as an afterthought rather than a core design element.

The spectral range was narrow and optimized only for certain Spectrum Composition, reducing flexibility for experimental needs.



Photos of the system SoA at project launch

Design Goals and Constraints

Efficiency, Spectral Control, and Structural Adaptation

The redesign had to respect strict structural constraints while delivering superior lighting performance.

Key goals included:

- **Uniformity:** irradiance std. deviation <10%
- **PPFD:** >800 $\mu mol \cdot s^{-1} \cdot m^{-2}$ with specific SQD

These requirements guided an on-top design strategy supported by simulation and iterative optimization.

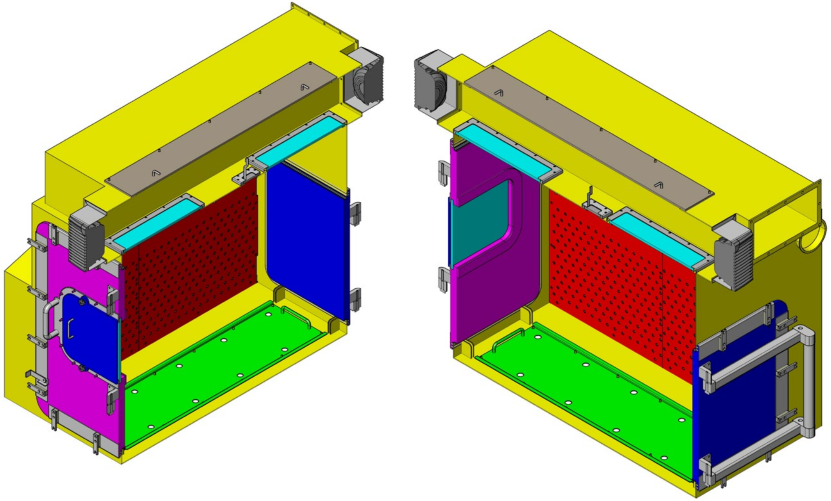
PaCMaN system overall view.

PaCMaN Model Analysis
Identifying Constraints and Intervention Areas

We started by analyzing the complete 3D model of the PaCMaN system to understand its structural and geometric constraints.

This step allowed us to identify critical limitations and define the areas where lighting components could be integrated without compromising the existing design.

The analysis served as the foundation for all subsequent simulation and optimization activities.



3D model analysis visualization.

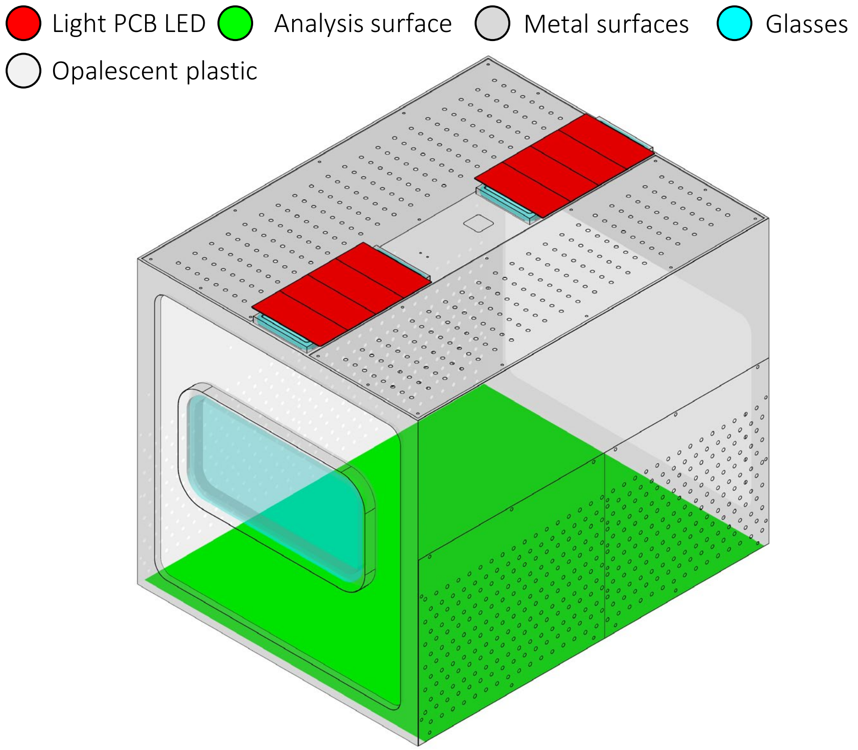
Optical Simulation Modeling
Accurate Material Assignment and Validation

We built a dedicated 3D model for optical simulations using advanced ray tracing techniques.

This approach allowed us to predict within the PaCMaN environment with high accuracy :

- **Light propagation**
- **Reflection**
- **Absorption**

Each surface was assigned realistic material properties, validated through on-site inspections, ensuring that simulation outputs closely matched real-world conditions.



3D Visualization of the RayTracing simulation layout.

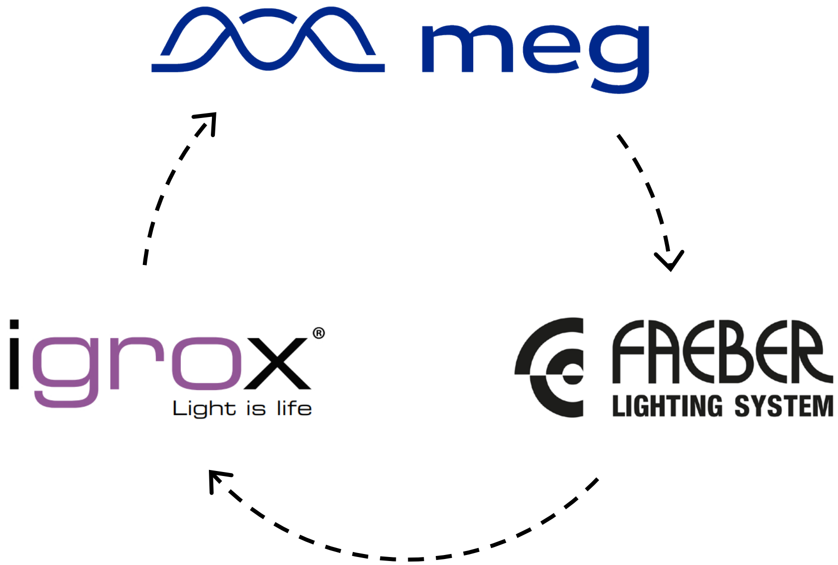
Supplier Dialogue and Component Definition

From LED Selection to Thermal Systems

We initiated a technical dialogue with specialized suppliers to define the core components of the lighting system.

This included mechanical fixtures, LED and PCB configurations, wiring and connectors, as well as active and redundant thermal management solutions.

In parallel, we worked on software and control interfaces to ensure seamless integration with PaCMaN’s architecture.



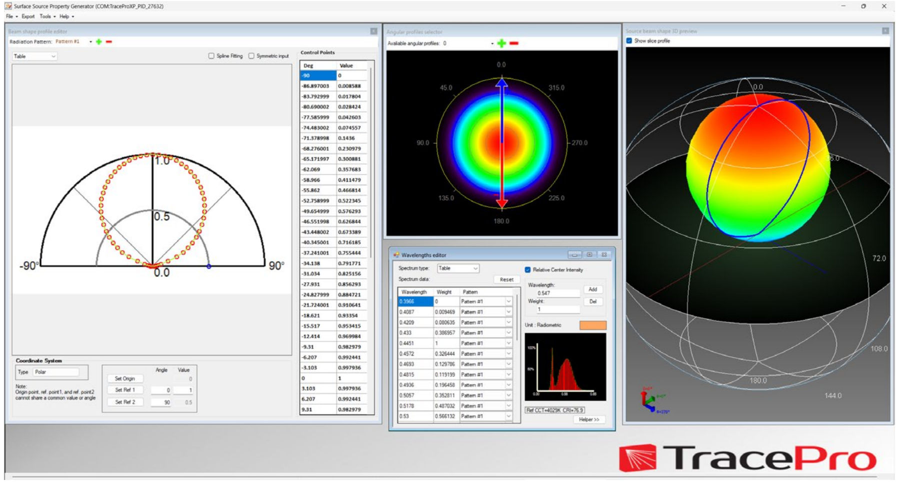
LED Characterization for Accurate Optical Simulation

From Datasheet Analysis to Realistic Modeling

To ensure that optical simulations in TracePro closely reflect real-world behavior, each LED was re-modeled with **high precision adapting the ray files provided by the manufacturer to our specific driving parameters.**

This process relied on an **in-depth analysis of manufacturer datasheets,** extracting critical parameters such as spectral power distribution, radiant flux, and angular intensity profiles.

By incorporating these details into the simulation environment, we achieved **highly reliable predictions,** reducing the need for physical prototyping and accelerating the design process.



RayFiles adaption inside TracePro source builder.

Simulation and Optimization

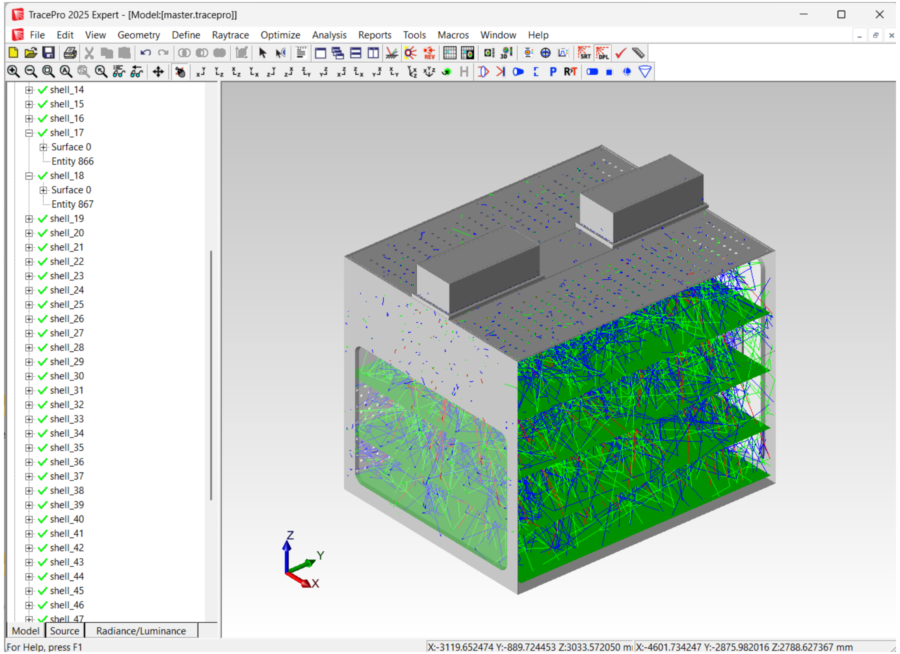
Iterative Design for Spectral and Geometric Accuracy

We integrated the selected LEDs into the simulation model and ran iterative ray tracing analyses to refine the design.

This process focused on:

- **Defining analysis surfaces** for accurate PPFD mapping
- **Optimizing LED geometry and positioning** to minimize hotspots
- **Configuring spectral channels** to achieve target R:B ratios
- **Validating PPFD values** in critical zones against performance goals

The result was a preliminary design that balances efficiency, uniformity, and spectral flexibility through a validated, multidisciplinary approach.



RayTracing simulation carried out in TracePro.

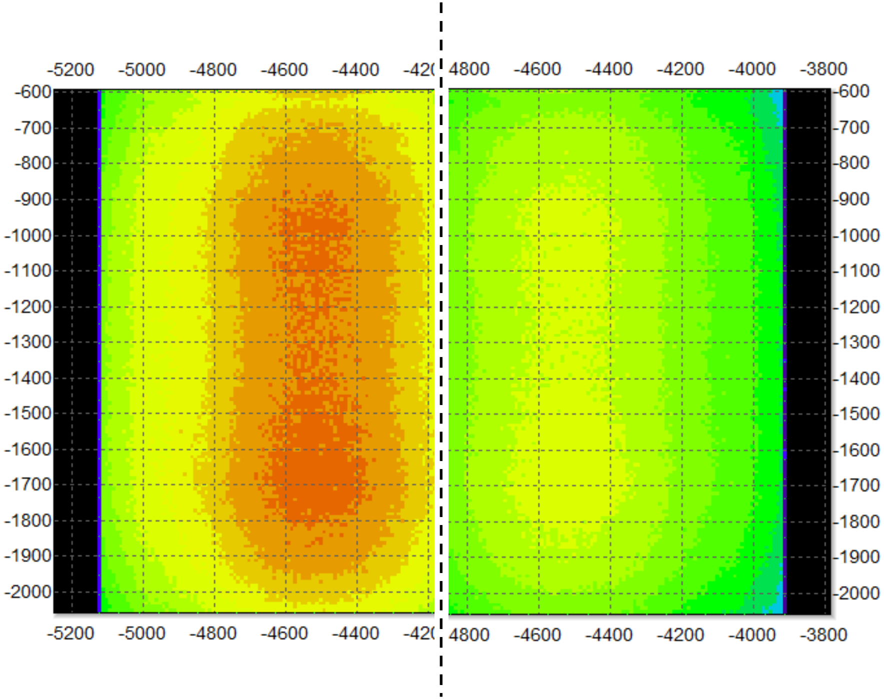
Irradiance Mapping Simulations

Virtual design validation through predictive irradiance maps

Optical simulations supported the entire light engine development, allowing us to anticipate light distribution and make **informed decisions before physical prototyping.** Through irradiance maps we managed to:

- **Optimize LED layout** for uniformity and hotspot reduction
- **Achieve PPFD targets** quickly and effectively

In this way, simulation became a central design tool, reducing both time and cost.



Before and after simulation-driven optimization.

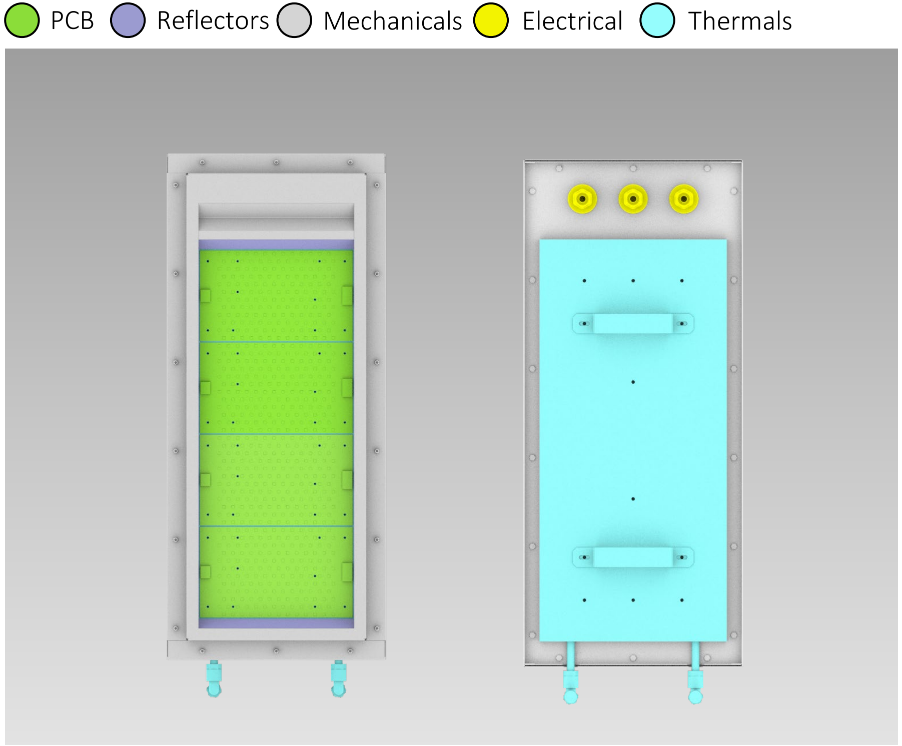
Technical Specifications

LED Arrays, PCB Design, and Integrated Sensors

The Custom Light Engines were built with high-performance components to ensure reliability and precision:

- **LEDs:** Samsung LH351H series in Red (660 nm), Blue (450 nm), Far-Red (730 nm), and White (5700K)
- **PCBs:** Metal-core boards (196 × 116.5 mm) for efficient heat dissipation
- **Connections:** tool-less terminals for secure and modular wiring
- **Sensors:** Integrated temperature sensors for real-time monitoring
- **Thermal Interface:** Optimized for active cooling systems

These specifications guarantee spectral flexibility, thermal stability, and long-term operational safety.



Front and back of the Custom Light Engines

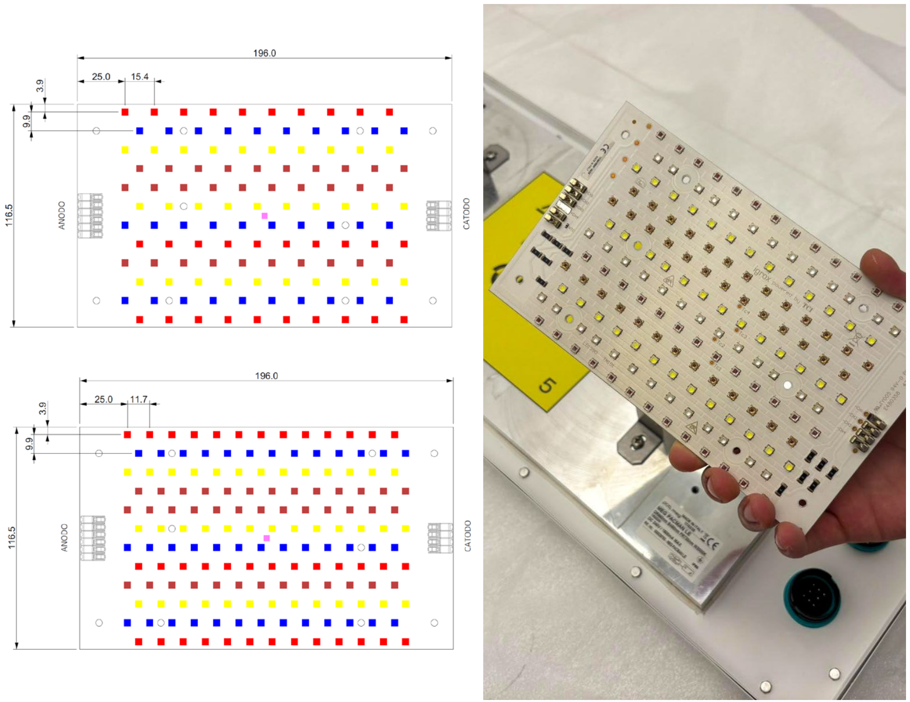
PCB Design & Features

High-Performance, Tunable Spectrum Platform

The custom PCB integrates **156 horticultural LEDs** distributed across four independent channels (Red 660 nm, Blue 450 nm, Far Red 730 nm, White 5700 K).

The staggered layout ensures uniform irradiance, while the **metal-core substrate** provides efficient thermal conduction and mechanical stability.

This design guarantees **spectral flexibility, durability, and consistent performance** under demanding conditions.



Iterations and final design of integrated PCB.

Mechanical Architecture

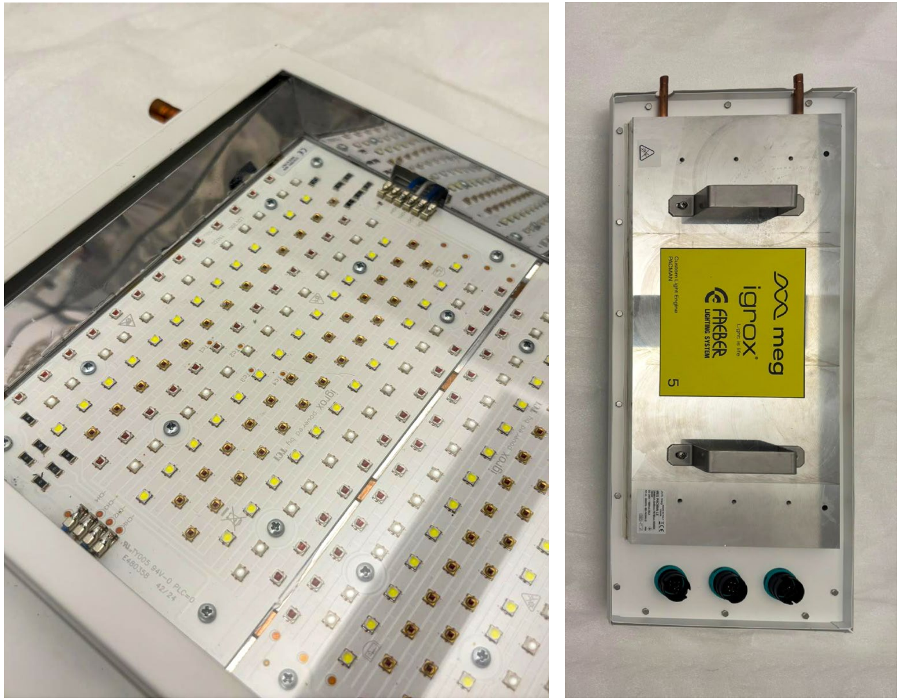
Compact, Modular, and Retrofit-Compatible

The Light Engine frame was engineered to fit seamlessly within PACMaN’s existing shell, avoiding structural modifications.

Key features include:

- **Steel housing and aluminum cold plate** for rigidity and heat dissipation.
- **Integrated routing** for power, data, and cooling lines.
- **Quick-release mounts** for simplified maintenance.

This modular approach ensures **robustness, ease of integration, and long-term reliability**.



Details of the Light Engine.

Thermal Interfaces

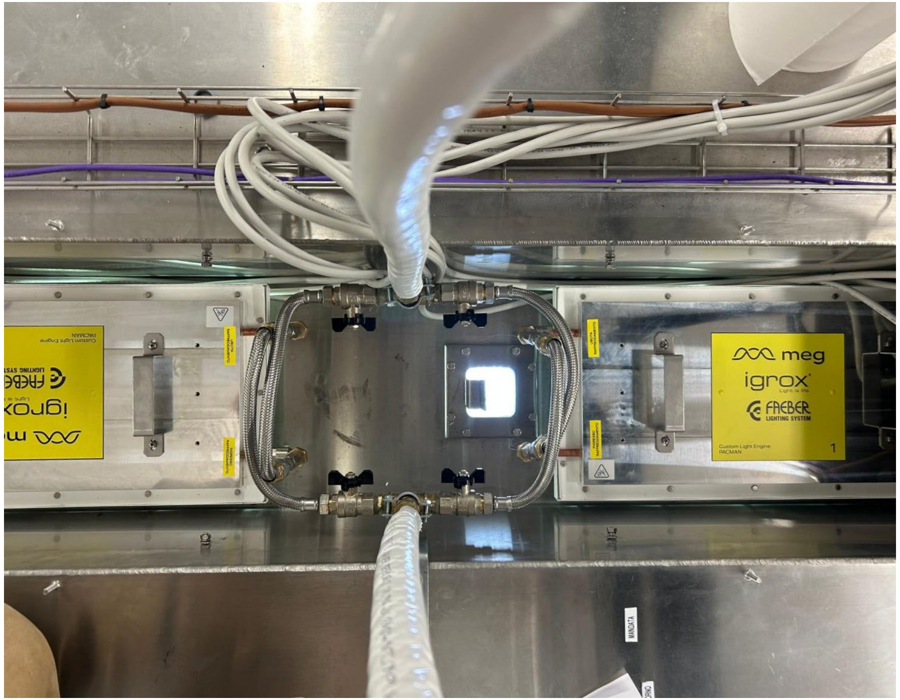
Reliable and Service-Friendly Integration

Efficient thermal management is critical for LED system performance.

Our interfaces combine high thermal conductivity with service-friendly design:

- **Quick-Release Connectors:** Light engines can be easily disconnected, including thermal connections.
- **Maintenance Isolation:** Input and output can be isolated to allow safe servicing without leaks.
- **Leak-Proof Design:** Connectors remain secure and leak-free when detached.

Reliable, easy maintenance ensuring minimal downtime in case of a failure.



Top view of thermal interfaces.

Optical Performance Validation

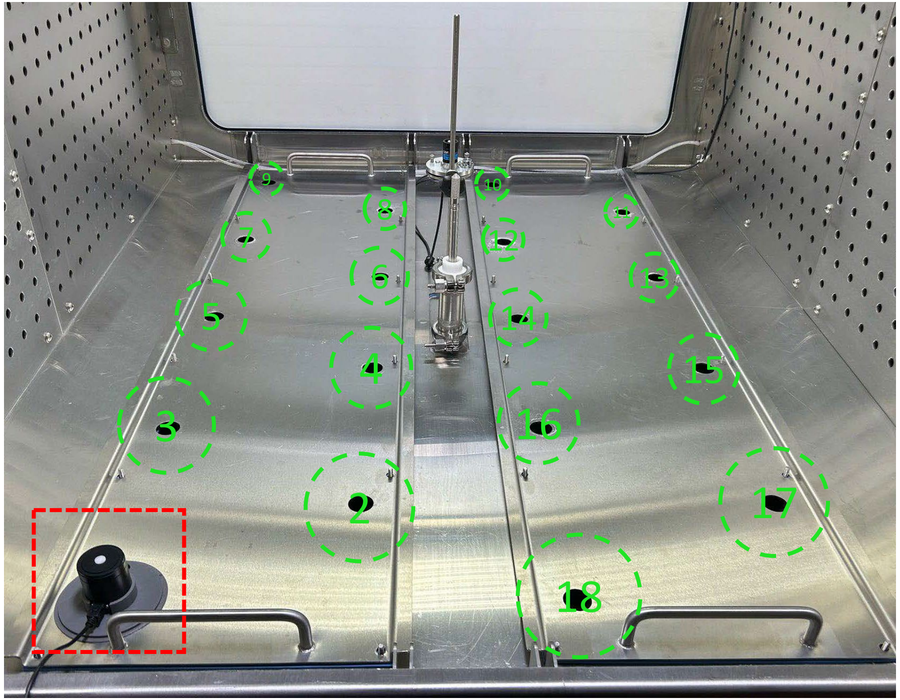
From Simulation to Measured Excellence

The PACMaN lighting system was validated through **on-site spectroradiometric measurements**, ensuring that performance metrics reflect actual operating conditions.

Results confirmed:

- **PPFD levels consistently above 800 µmol·s^{-1}·m^{-2} with specific SQD**
- **Uniformity standard deviation < 7%**

This demonstrates that the system not only meets but exceeds design goals, delivering **reliable, reproducible lighting conditions for controlled-environment research**.



Spectroradiometer and measuring points.

Process Summary
Turning Constraints into Robust, Validated Solutions

Our approach transformed initial limitations into design opportunities.

Through iterative simulations, multidisciplinary collaboration, and close coordination with suppliers, we developed a solution that is robust, integrated, and fully validated.

This process ensured that every decision—from geometry to spectrum—was driven by performance and reliability.

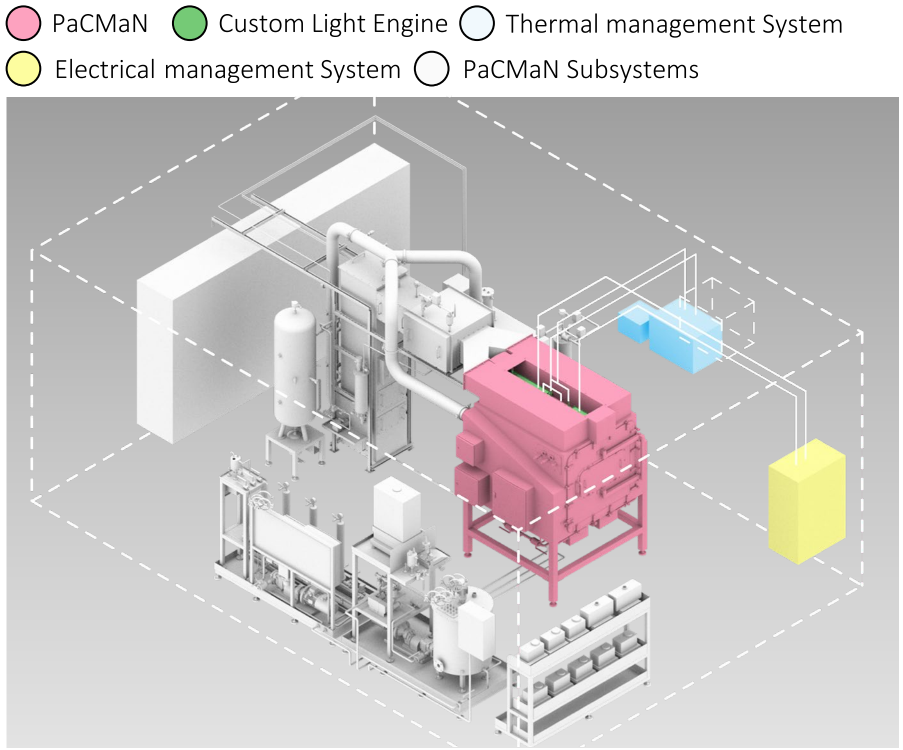
Experimental cultivation being carried out in PaCMaN

System Integration
Hardware and Software Synergy with PaCMaN

The final step was integrating the custom light engines into the PaCMaN system. This involved:

- **Functional and logical diagrams** to map hardware and control flows
- **Collaboration with ENGINSOFT** for seamless mechanical and software alignment
- **Full integration of lighting control with PaCMaN's PLC** and automation systems
- **Validation of interoperability** between hardware and software

This integration ensures that lighting is no longer an accessory but a core element of PaCMaN's operational architecture.



System integration 3D visualization.

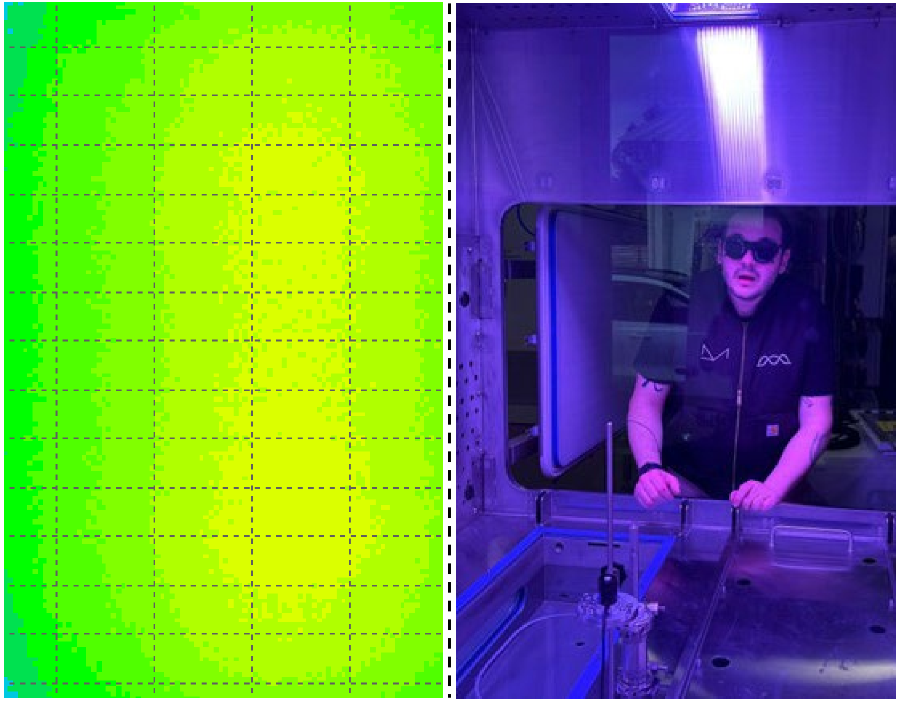
Measurement Methodology

Spectroradiometers Readings and TracePro Simulations

To validate system performance, we combined digital simulations with physical measurements:

- **Ray tracing simulations** in TracePro to inspect irradiance and uniformity under different SQD configurations
- **Spectral and PPFD measurements** using a CSS-45 spectroradiometer across 18 reference positions
- **Cross-validation** between measured and simulated data to ensure accuracy and reliability

This dual approach provided a robust foundation for performance benchmarking and validation.



TracePro simulation; Irradiance measurement being carried out.

Red – 660 nm – 100%

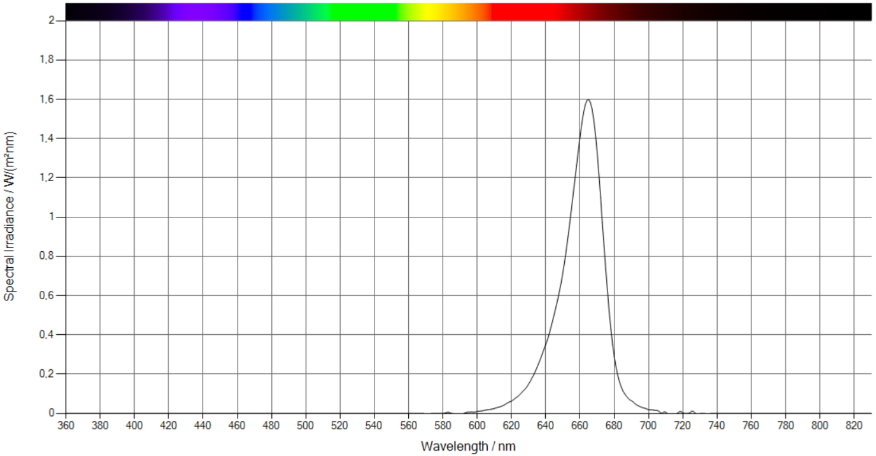
Replaced Lighting Fixtures

2-RED-660

100%

---	1	2	3	4
1	199	-	206.2	-
2	-	220.2	-	218.1
3	229.8	-	237.1	-
4	-	252.9	-	262.1
5	277.2	-	266.6	-
6	-	272.5	-	281.5
7	281.8	-	278.1	-
8	-	271.2	-	260.9
9	243.7	-	249.5	-

ave	250.47
min	199.00
max	281.80
min/max	0.71
min/ave	0.79
std dev	26.65
% std dev	10.64



Target surface irradiance map – µmol/s/m^2 PAR range; sample spectrum.

Red – 660 nm – 100%

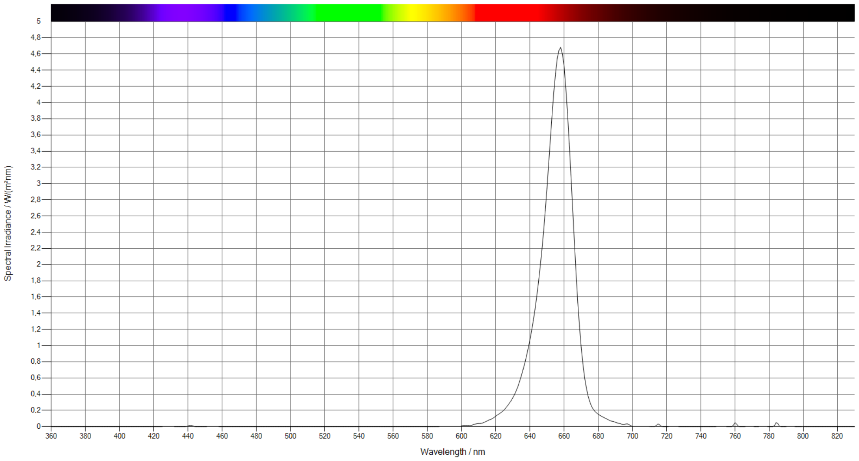
Custom Light Engines MEG Science

2-RED-660

100%

---	1	2	3	4
1	534.4	-	581.3	-
2	-	567.3	-	543.9
3	572.7	-	542.8	-
4	-	512.1	-	552.7
5	510.1	-	557.4	-
6	-	543.6	-	514
7	541.6	-	518.5	-
8	-	496.6	-	524.9
9	492.6	-	514.9	-

ave	534.52
min	492.60
max	581.30
min/max	0.85
min/ave	0.92
std dev	25.80
% std dev	4.83



Target surface irradiance map – µmol/s/m² PAR range; sample spectrum.

Quantitative Conclusions

Enhanced PPFD, Uniformity, and Spectral Control

The validation phase confirms that the MEG system delivers:

- **Double the average PPFD** compared to the reference solution.
- **Superior uniformity,** reducing variability and improving reproducibility.
- **Full spectral control,** enabling advanced research protocols and adaptive lighting strategies with high irradiance

These results demonstrate a significant leap forward in controlled-environment lighting.

Experimental cultivation being carried out in PaCMaN.

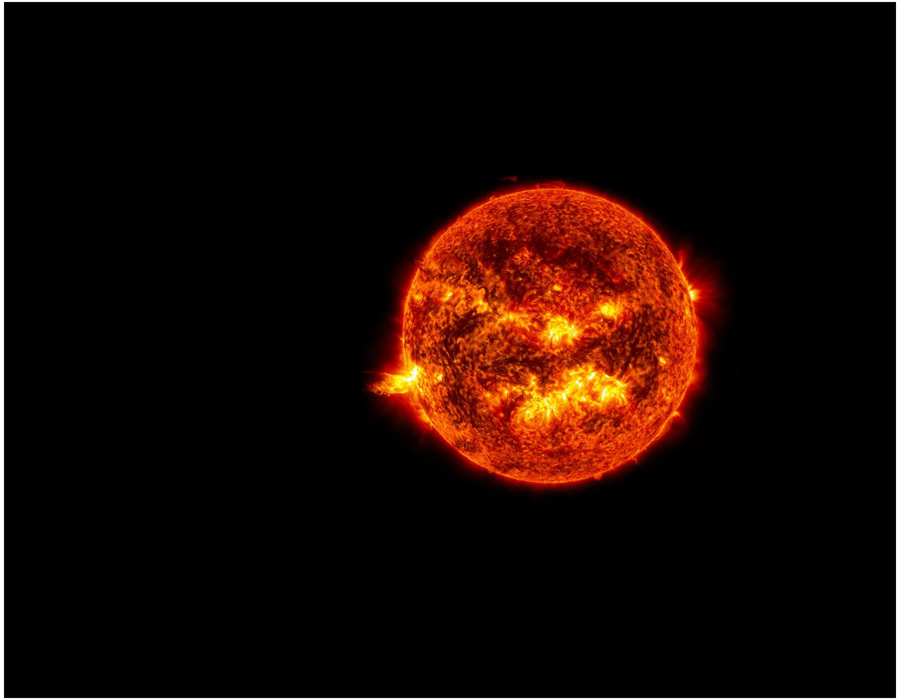
The “Light First” Approach

From Accessory to Foundational Design Principle

The shift begins with rethinking the role of light in system design. This means:

- Moving away from the traditional view of lighting as an accessory added after structural and mechanical decisions
- Adopting a **“Light First”** approach, where illumination becomes a core design principle
- Integrating light from the **earliest stages** to turn it from a constraint into a strategic lever for **performance, efficiency, and scalability**
- Redefining growth chambers and photobioreactors as systems inherently optimized for both **biology and engineering**

This transformation ensures that lighting is no longer an afterthought, but a foundational element of next-generation controlled environments.



The Sun.

Acknowledgments

ENGINSOFT and MELiSSA Foundation

We gratefully acknowledge the contributions of our partners:

- **ENGINSOFT,** for engineering support
- **MELiSSA Foundation,** for their vision and commitment to advancing life-support technologies.

Together, we have demonstrated what is possible when **science, engineering, and innovation converge.**

Thanks for your attention

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