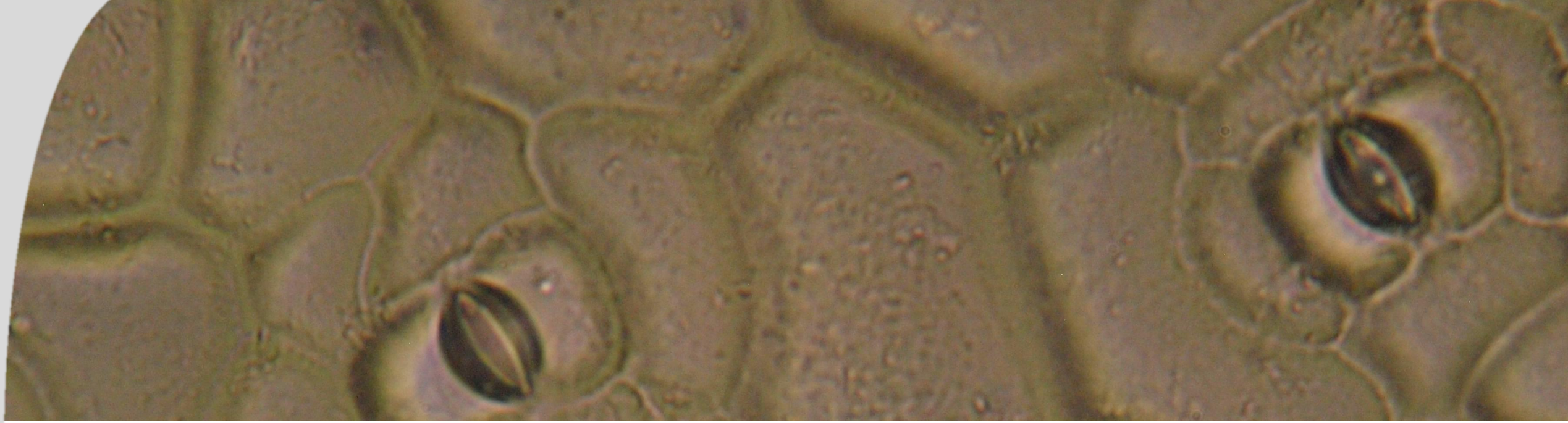


green4indoor |
ENERGY-EFFICIENT INDOOR CLIMATE CONTROL WITH PLANTS

Dr. Annette Bucher | HSWT
University of Applied Sciences
Dr. Michaela Reim | CAE
Center for Applied Energy Research

WEIHENSTEPHAN · TRIESDORF
University of Applied Sciences

gefördert durch
DBU
Deutsche
Bundesstiftung Umwelt
www.dbu.de

CAE | Center for Applied Energy Research

WEIHENSTEPHAN · TRIESDORF University of Applied Sciences

zero carbon

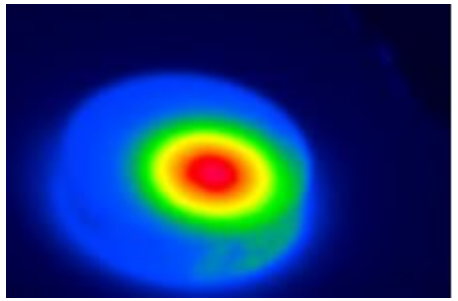
- 50 Employees
- 3700 qm Research Area
- Climate-Research-Facility
- Info-Center (public access)
- Green Box

Workgroups

Climate Neutral Buildings and Cities

Smart Functional Materials

Advanced Thermal Management



Sensors for Energy and Hydrogen Technology

Energy System Management and Technology Integration

HSWT | Hochschule Weihenstephan-Triesdorf

Research Facilities

Institute of **Horticulture** (IGB)

With Schlachters Research Station for **Pomiculture** and ASC **Smart Indoor Farming**

Institute of **Food Technology** (ILM)

Institute of **Ecology and Landscape** (IÖL)

Centre for Research and Knowledge Transfer (ZFW)

Competence Centre for **Digital Agriculture** (KoDA)

Institute for **Biomass research** (BIT)

2022:

191 research projects conducted, nearly € 13 mil. of third part funding

Outline

- Goals of the project
- Methods
- Results
  - Selection of plants | Identification of plant species with high transpiration rate
  - Optimization of the two greening systems with regard to controllability of the evapotranspiration rate and cooling capacity
  - Investigation of the greening systems under defined conditions
- Summary and Outlook

Outline

- **GOALS OF THE PROJECT**
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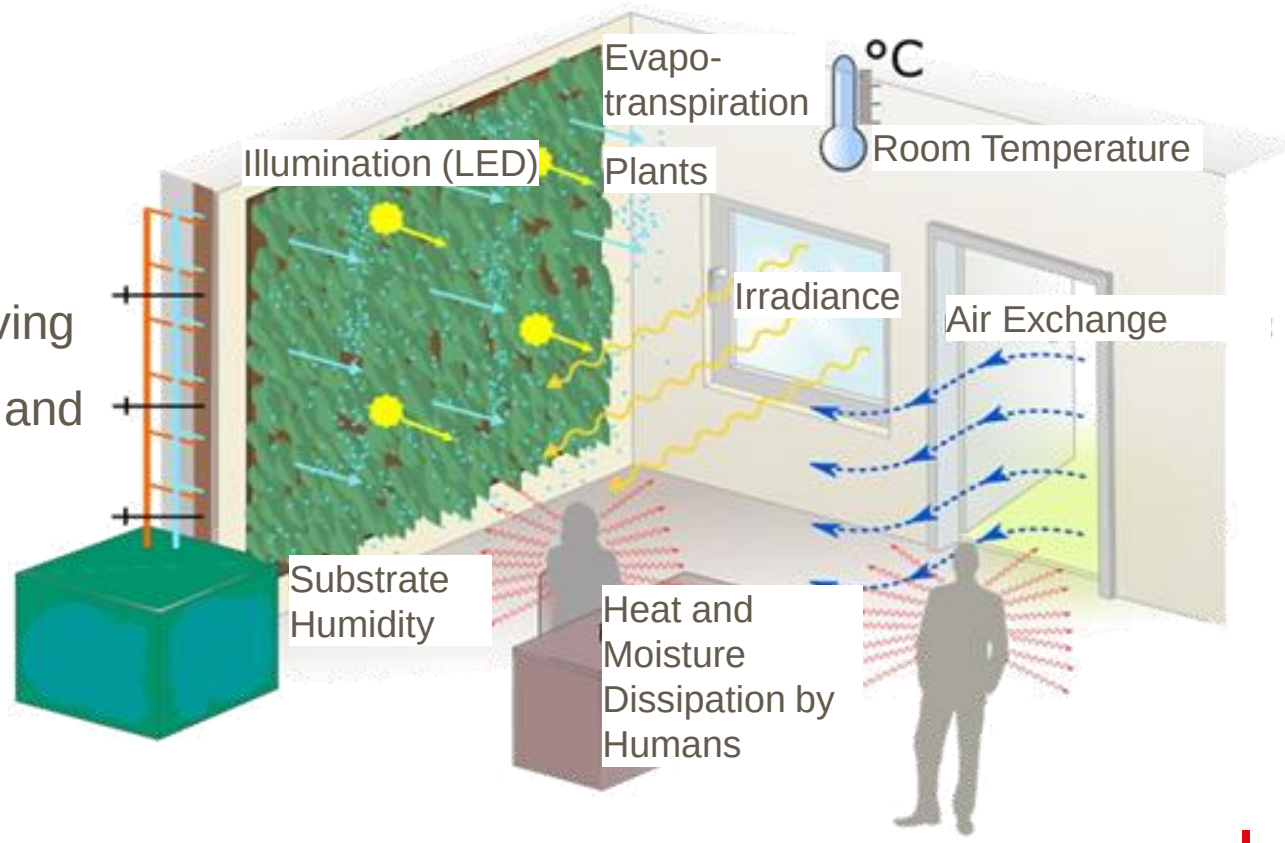
- Summary and Outlook

Goals of the project

- Support of room air conditioning by functional, vertical greening:
  - Humidification of dry air in winter
  - Reduction of air temperature by evapotranspiration in summer → energy saving
- Optimization of system design, plant selection and irrigation
- Determination of the contribution of plants to evapotranspiration
- Extension of the systems by adding an unvegetated evaporation surface
- Development of a control strategy for adapted evapotranspiration rate and cooling capacity



Outline

- Goals of the project
- **METHODS**
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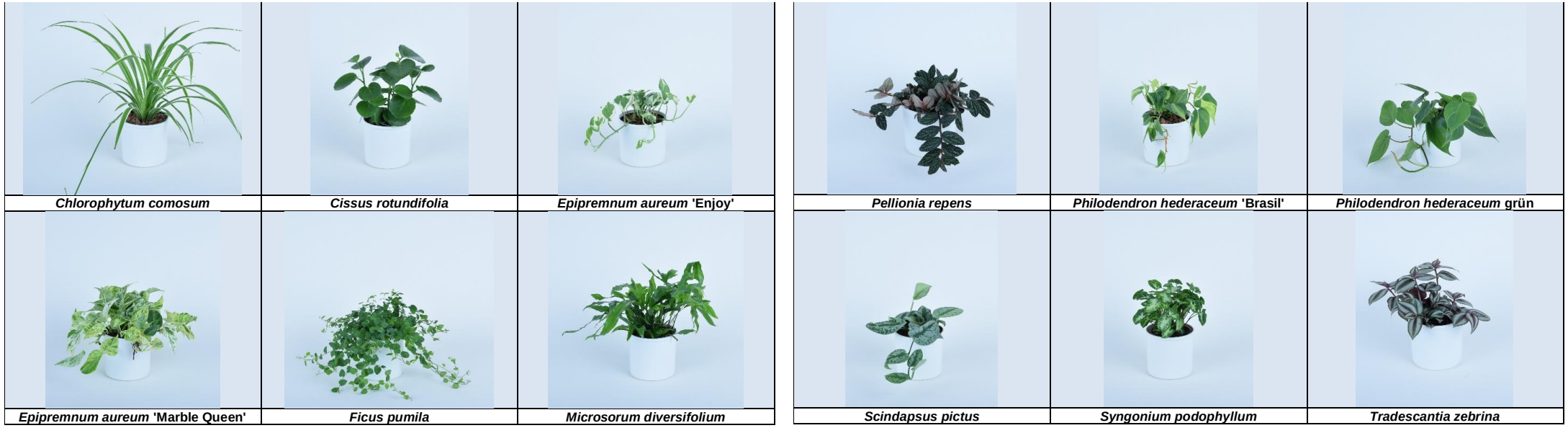
Methods

- Identify plant species with high transpiration rate at low humidity levels
- Testing the water release of greening systems and additional evaporation area
- Investigation of suitable sensors for controlling irrigation and humidity regulation
- Development of a maintenance strategy for the vertical greening systems
- Testing of the further developed greening systems under defined room conditions

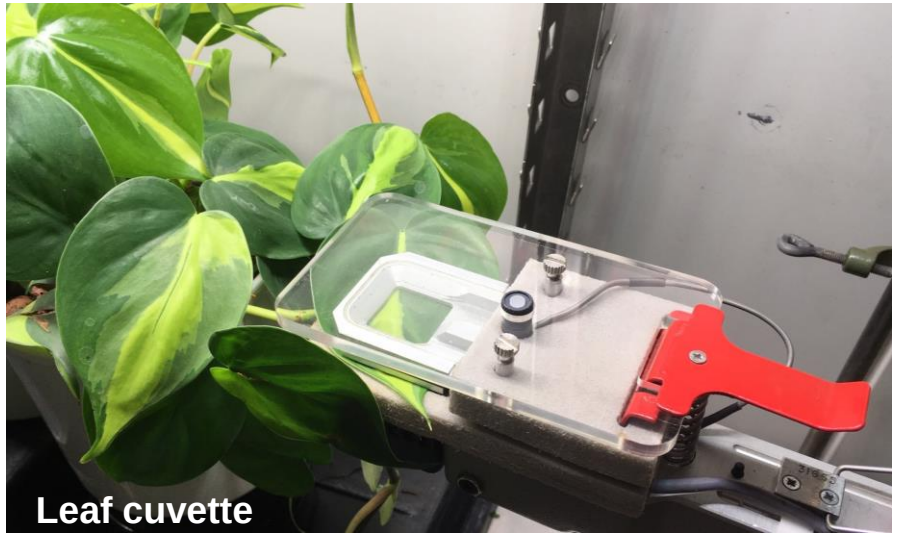


Plant species used for the measurement of photosynthesis parameters

Methods

Measurement of photosynthesis parameters

- Transpiration rate (E, mmol m^{-2} s^{-1})
- Stomatal conductivity (Gs, mol m^{-2} s^{-1})
- With LCpro-SD and LCpro T (ADC BioScientific)
- Adjustment of humidity, temperature, CO_2, PAR in the leaf cuvette
- Gas analysis with non-dispersive infrared technology (NDIR)



Methods

Selection criteria greening system

- Positive practical experience regarding horticultural suitability, durability, acceptance
- Regulation of irrigation and water delivery possible
- Large evaporation surface
- Preferred mineral substrates
- Passive evaporation

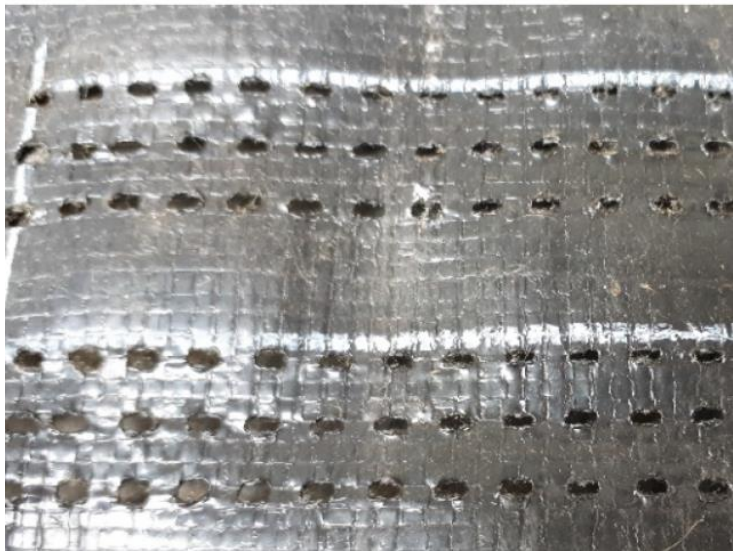
Living Wall Indoor (Vertiko GmbH): felt-fleece pockets filled with mineral growing medium

Wallflore-Prototyp (Cloudgarden/Ruof): Rockwool covered with perforated HDPE film

Methods

Optimisation of perforation design HDPE film

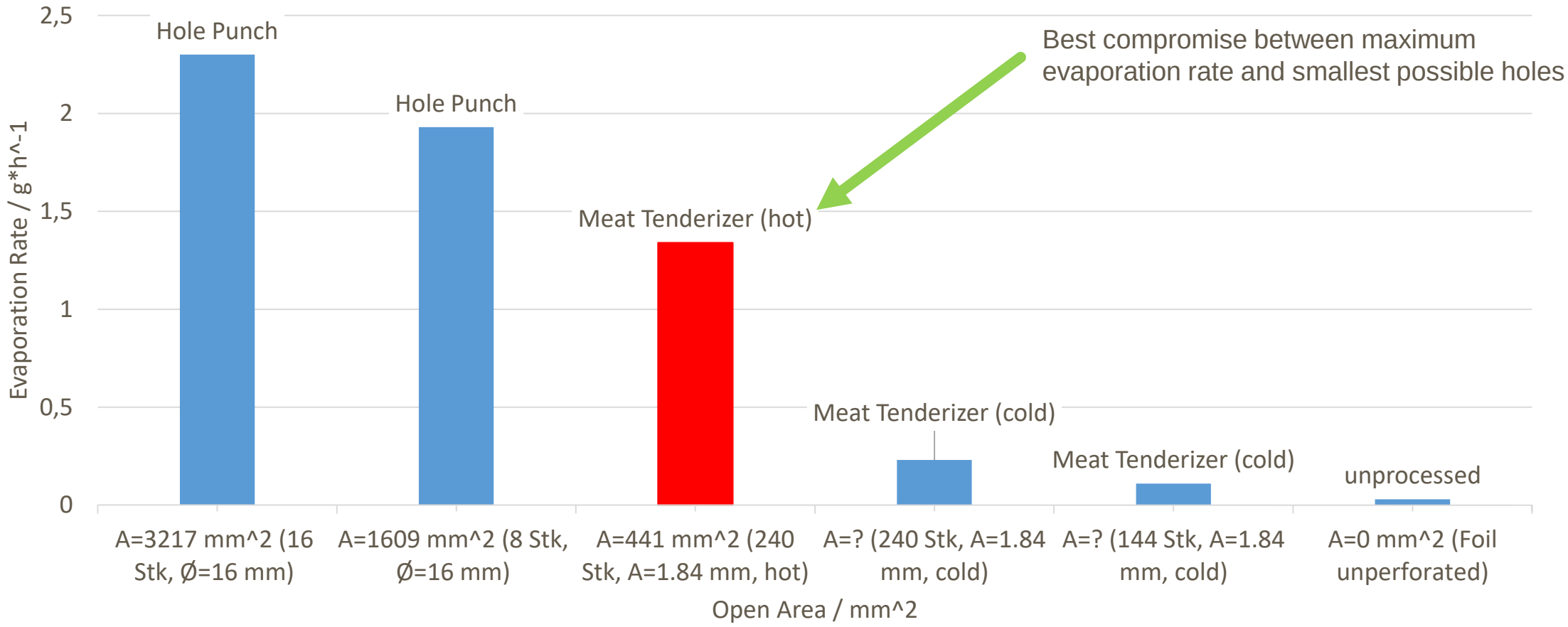
- Specific evaporation rate of the modified HDPE film determined gravimetrically in the climatic chamber
- Perforation of the film of the Wallflore greening system with a meat tenderiser at selected positions
- Interior wall greening system equipped with perforated film



Methods

Optimisation of perforation design HDPE film

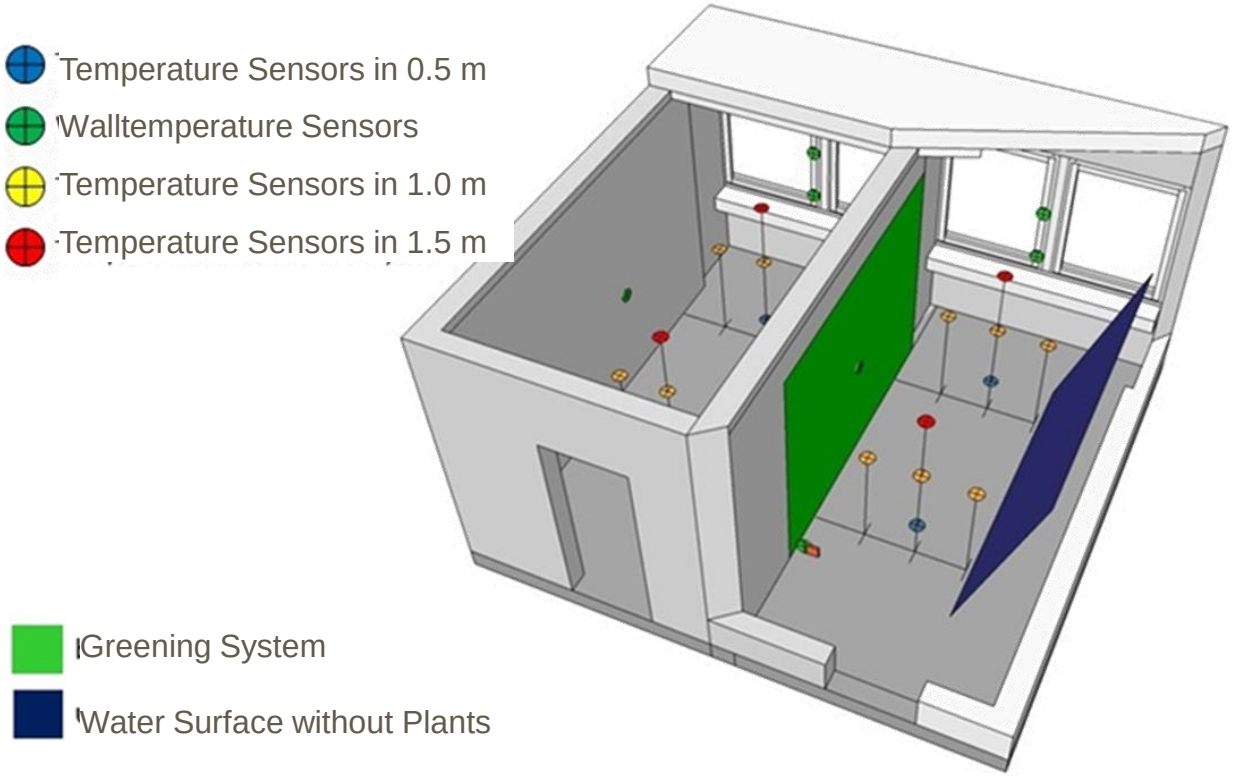
- Perforation HDPE film of Wallflore/Ruof System

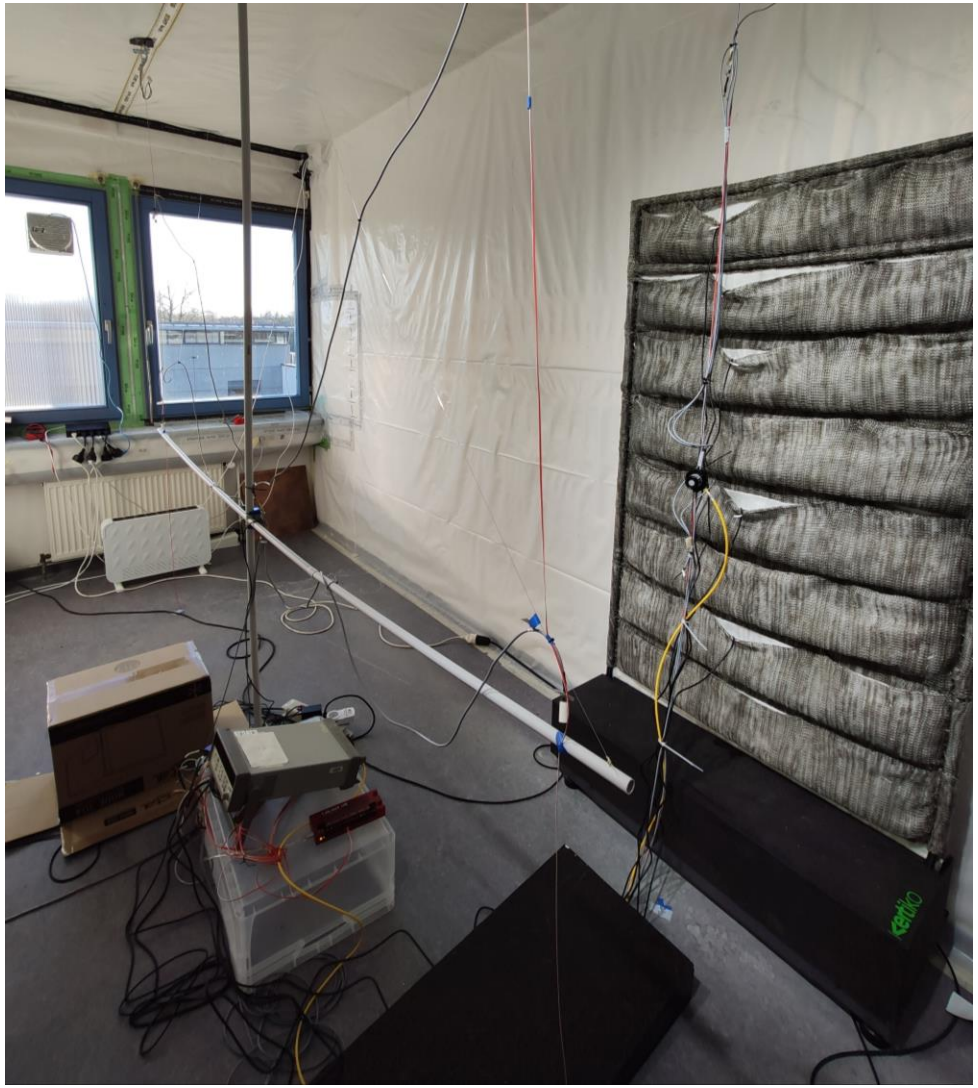


Methods

Structure of the twin measuring rooms with and without greening

Identical in construction | Thermally identical behavior | Hygric identical





Methods

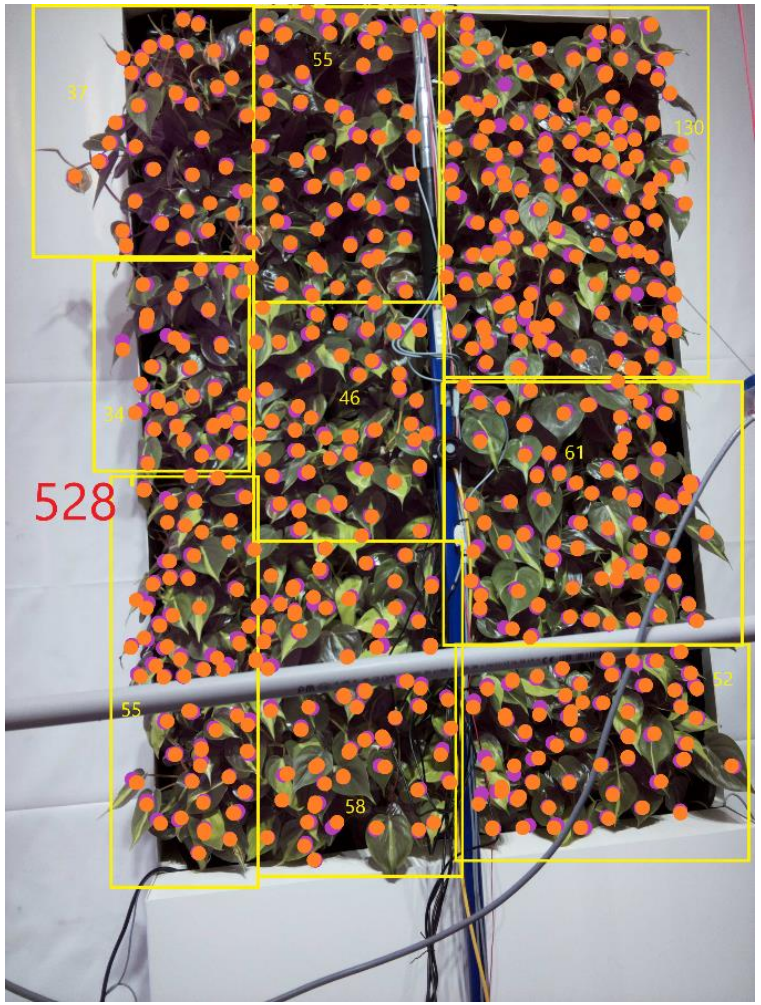
Structure of the twin measuring rooms with and without greening

- Testing of the further developed greening systems under defined room conditions
- Testing of the greening systems without plants (only wet growing media)

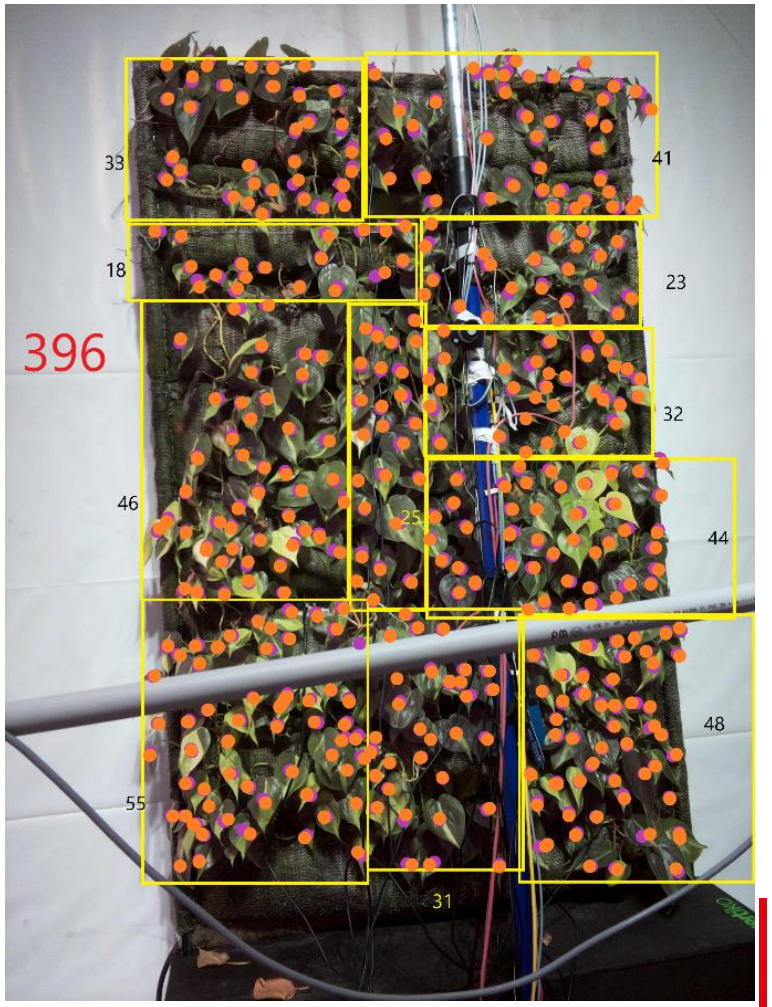
Methods

Determination of the number of leaves

- A grid of yellow rectangles was placed over the photographs and leaves in the rectangles were counted
- Counted individual leaves are marked with dots
- Adding up the number of leaves in all rectangles gives the total



Wallflore: 528 leaves



Vertiko: 396 leaves

Outline

- Goals of the project
- Methods
- **RESULTS**
  - Selection of plants | Identification of plant species with high transpiration rate
  - Optimization of the two greening systems with regard to controllability of the evapotranspiration rate and cooling capacity
  - Investigation of the greening systems under defined conditions
- Summary and Outlook

Results

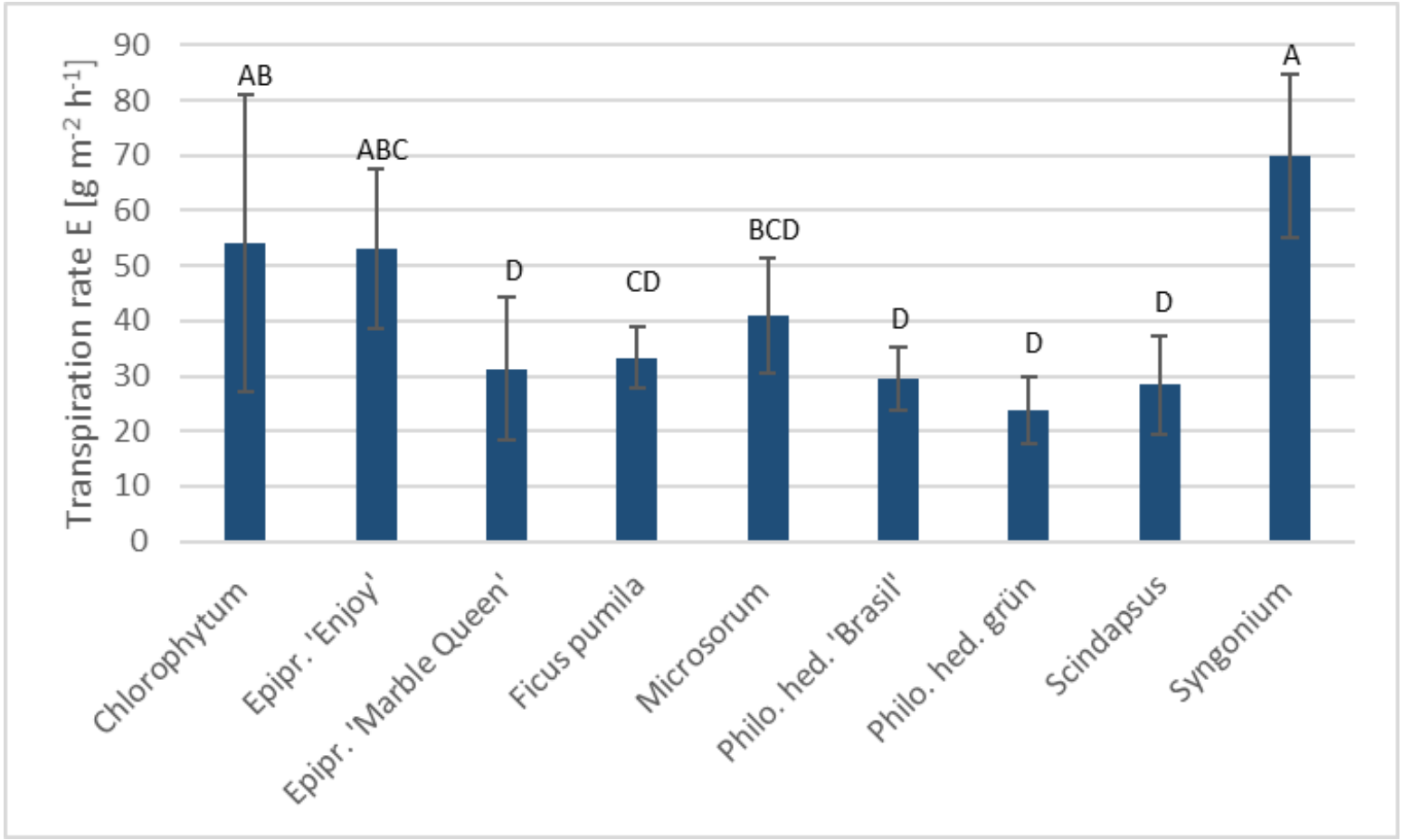
Factors influencing stomatal opening and transpiration

- Plant species
- Light (photosynthetically active radiation = PAR)
- Relative humidity (RH)
- Temperature
- Wind speed
- CO_2 concentration
- Season
- Growing media moisture

Stomata of *Philodendron hederaceum* `Brasil`

Results

PLANT SPECIES



Comparison of transpiration rate of different plant species when measured in summer.

Mean values (3 leaves of 3 plants each = 9 repl.) that do not have a common grouping letter are significantly different by Tukey's test ($p < 0.05$)

Results

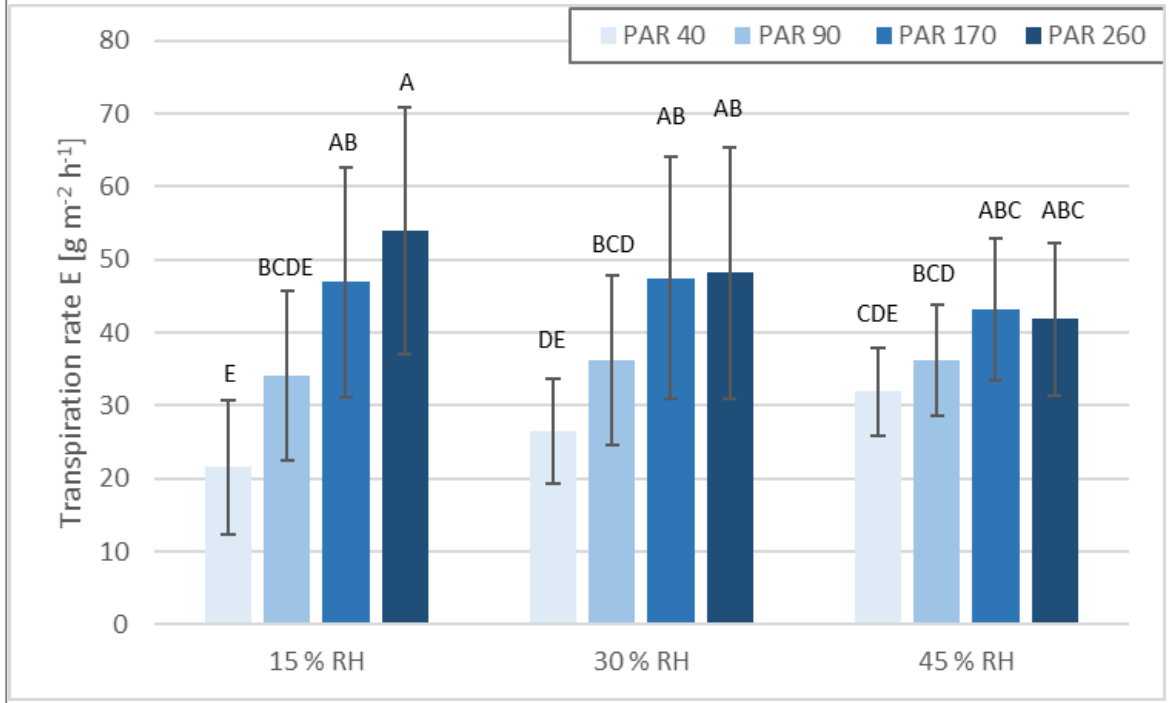
LIGHT (PHOTOSYNTHETICALLY ACTIVE RADIATION = PAR)

Inceasing transpiration with increasing light intensity:

- *Philodendron hederaceum `Brasil` and green*
- *Microsorum diversifolium*
- *Syngonium podophyllum*

No influence of light intensity on stomatal conductance and transpiration:

- *Ficus pumila*
- *Chlorophytum comosum*
- *Pellionia repens*
- *Epipremnum aureum* `Enjoy`
- *Scindapsus pictus*
- *Tradescantia zebrina*

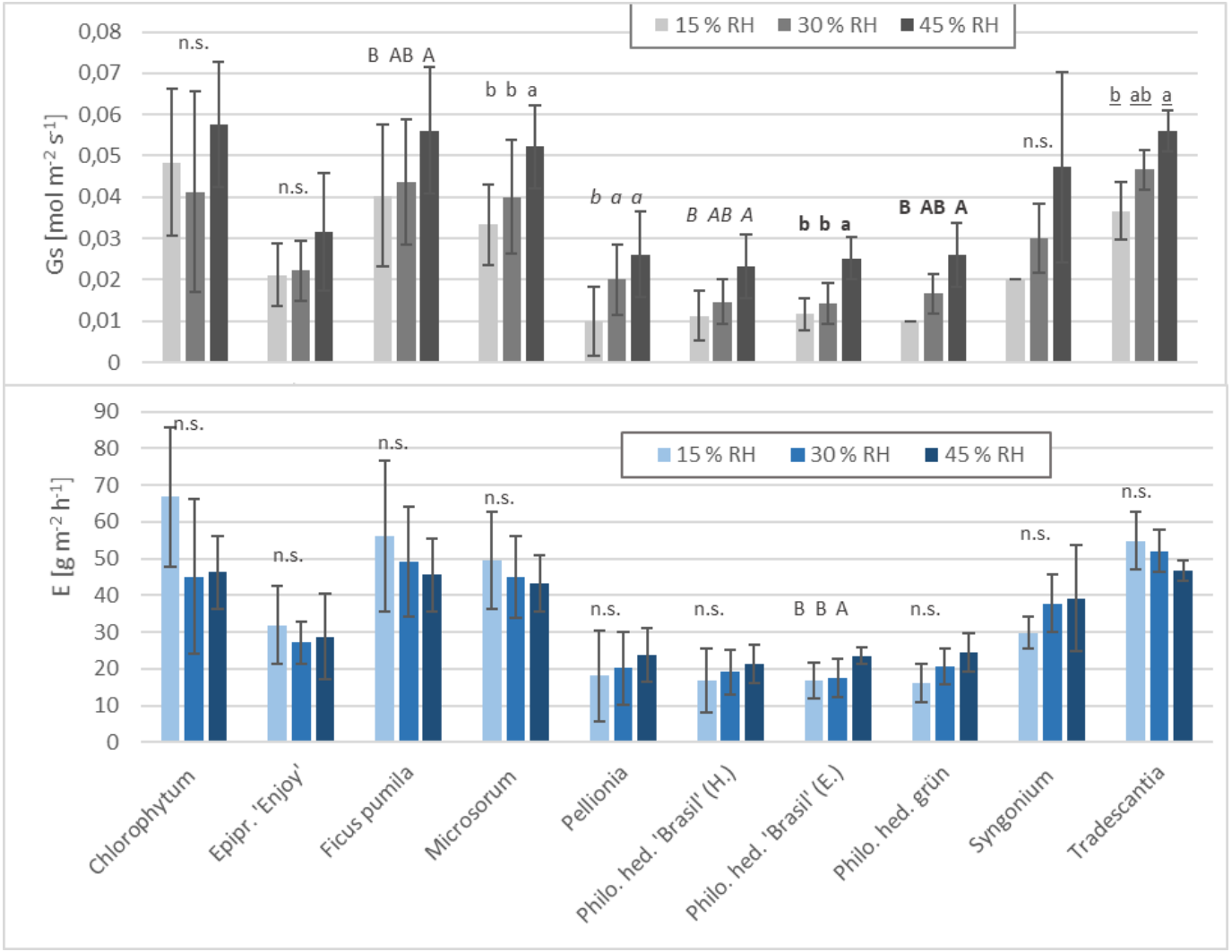


Comparison of stomatal conductance (left) or transpiration rate (right) of *Philodendron hederaceum* 'Brasil' at defined relative humidities (RH) and light intensities (PAR in µmol m^{-2} s^{-1}).

Mean values (3 replicates) that do not share a common grouping letter are significantly different by Tukey's test ($p < 0.05$) related to RH x PAR

Results

RELATIVE HUMIDITY (RH)



Stomatal opening is more sensitive to low humidity than transpiration

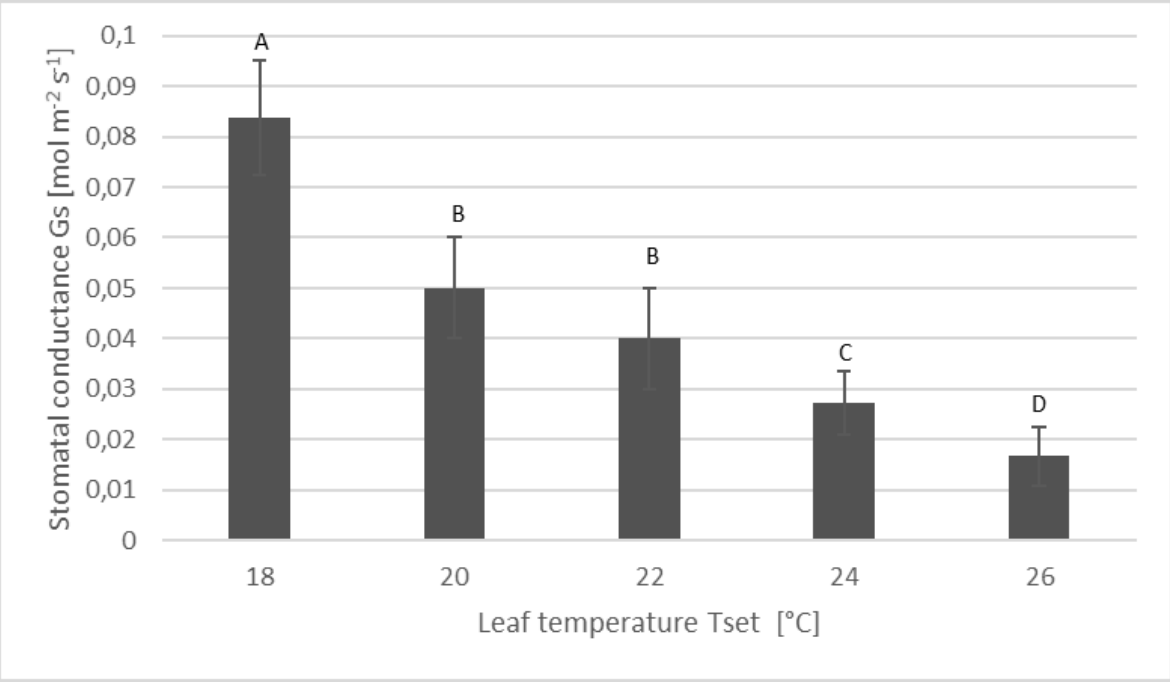
Comparison of stomatal conductance (above) or transpiration rate (bottom) of different plant species when measured in summer with defined humidities.

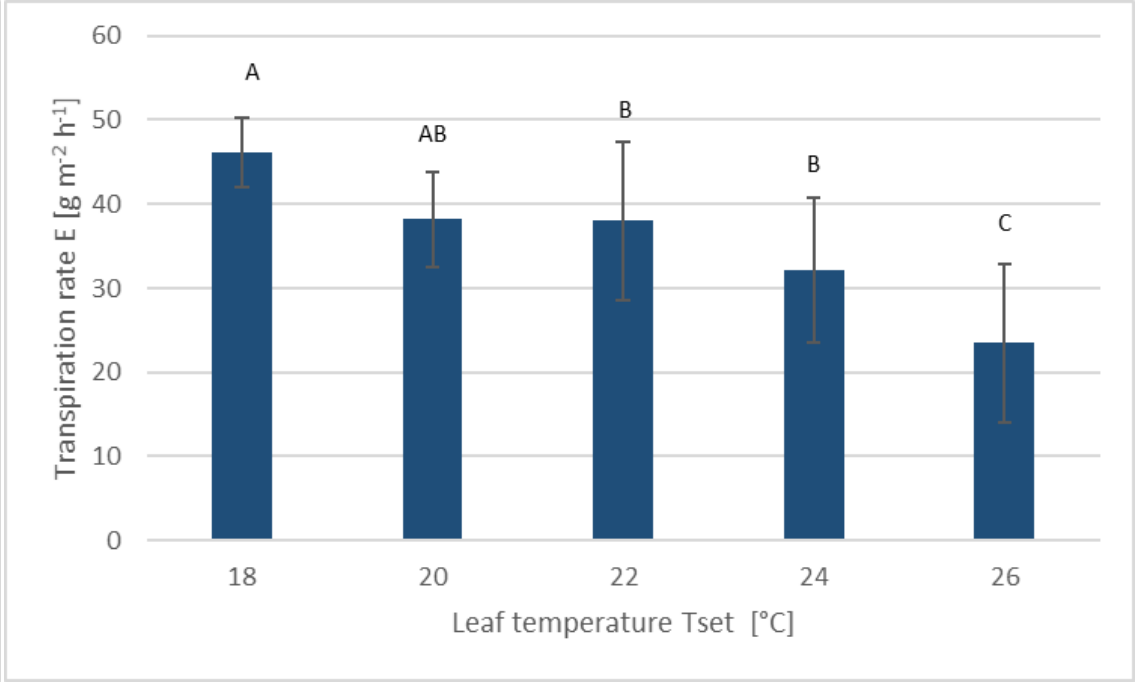
Mean values of one species (3 plants with 3 leaves each = 9 repl.), which do not have a common grouping letter, differ significantly in Tukey's test ($p < 0.05$)

Predominantly no response of the transpiration rate to low humidity in the leaf cuvette

Results

TEMPERATURE



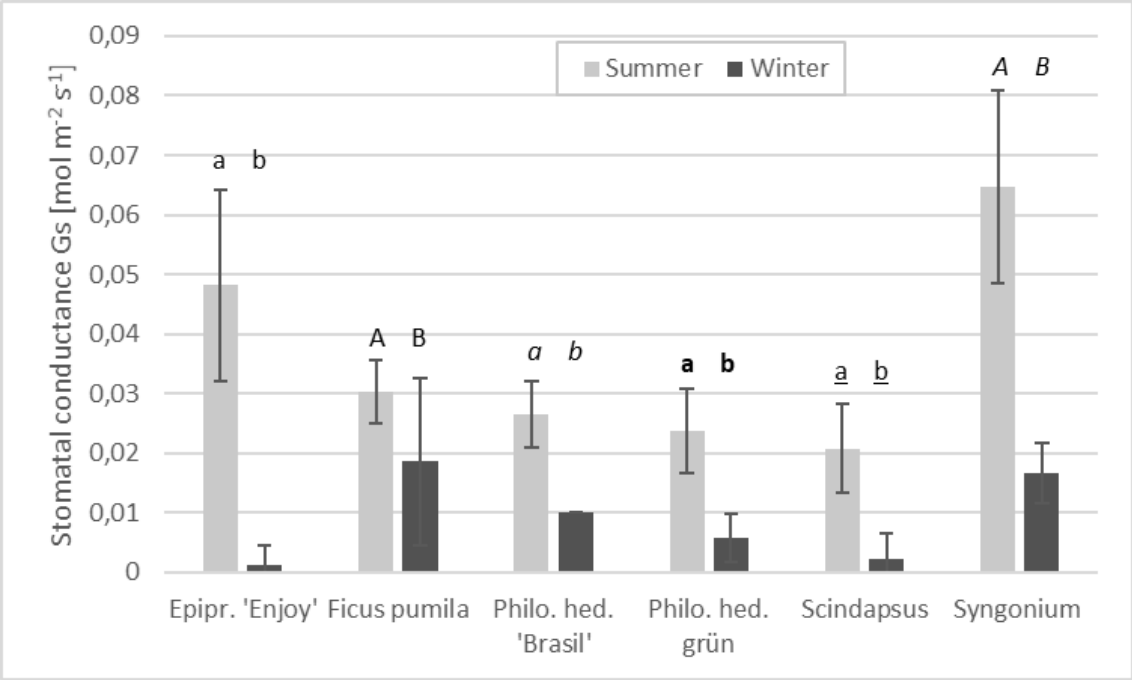


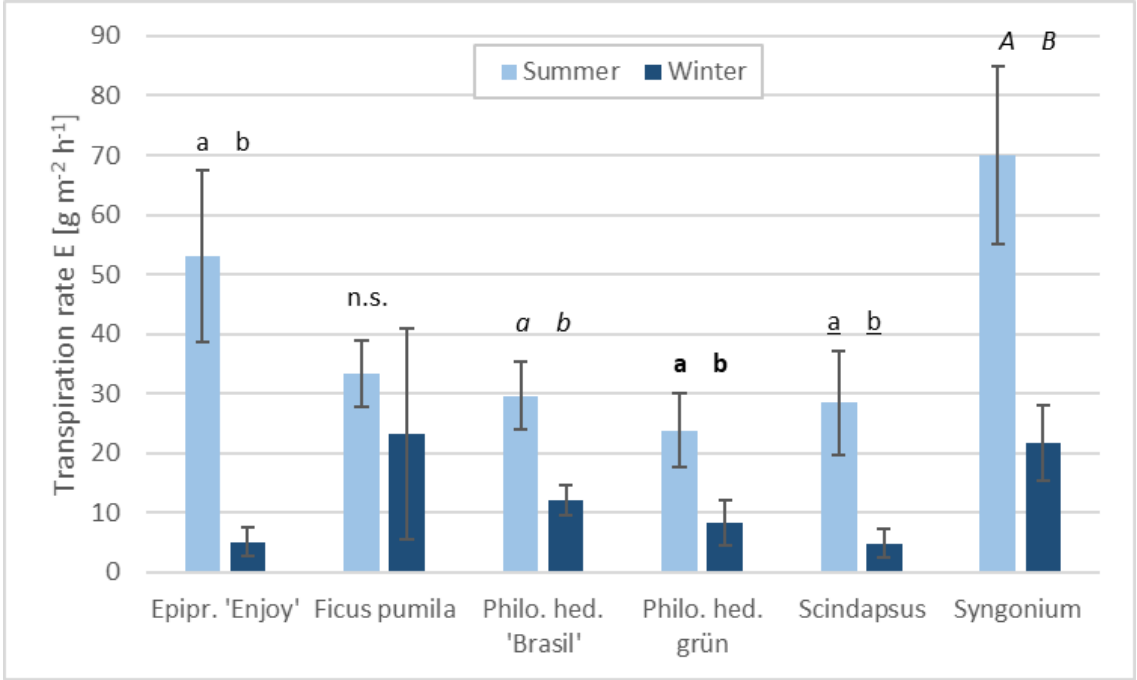
Comparison of stomatal conductance (left) or transpiration rate (right) of *Philodendron hederaceum* 'Brasil' at defined leaf temperatures.

Mean values (3 replicates) that do not share a common grouping letter are significantly different by Tukey's test ($p < 0.05$)

Results

SEASON



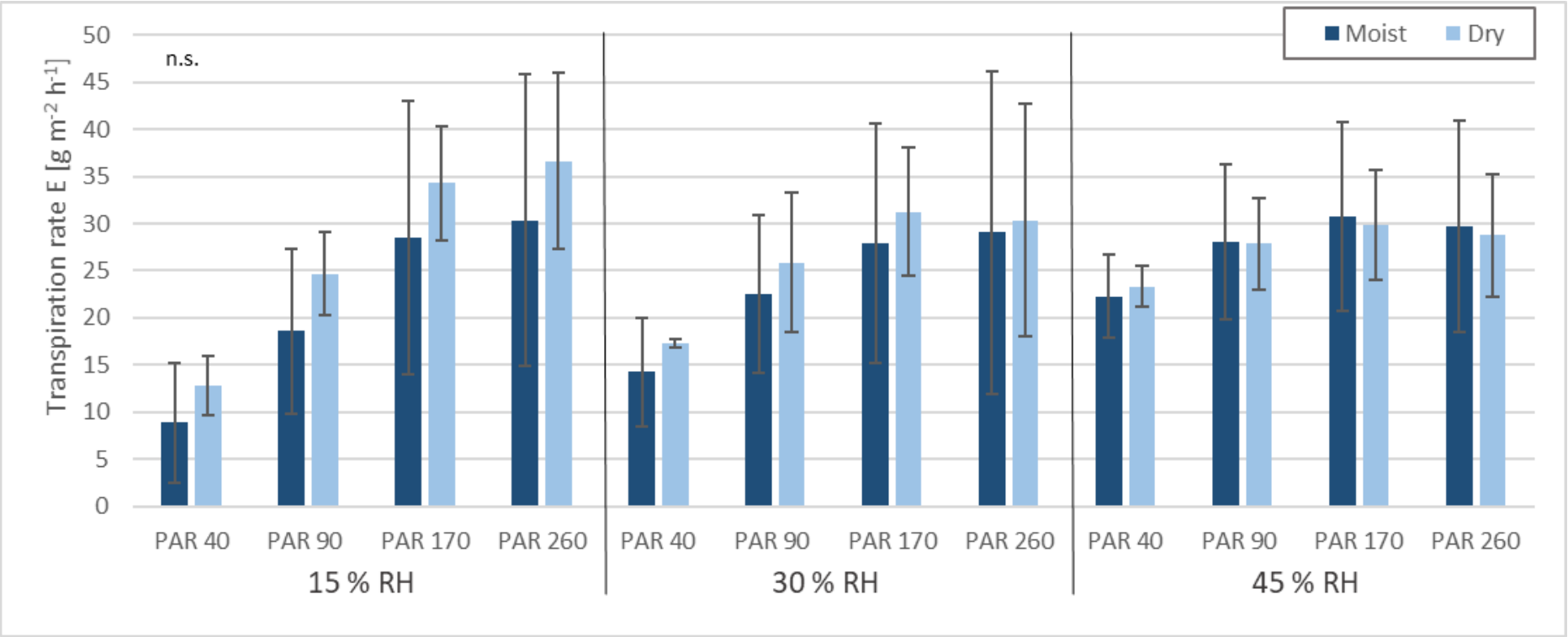


Comparison of stomatal conductance (left) or transpiration rate (right) of different plant species in summer and winter.

Mean values (3 plants with 3 leaves each = 9 repl.) that do not have a common grouping letter are significantly different by Tukey's test ($p < 0.05$)

Results

GROWING MEDIA MOISTURE



Comparison of transpiration rate of *Philodendron hederaceum* 'Brasil' at defined growing media moisture in combination with varied humidity (RH) and irradiance (PAR in µmol m^{-2} s^{-1}).

Mean values (2 repl.) that do not share a common grouping letter are significantly different by Tukey's test ($p < 0.05$)

Results

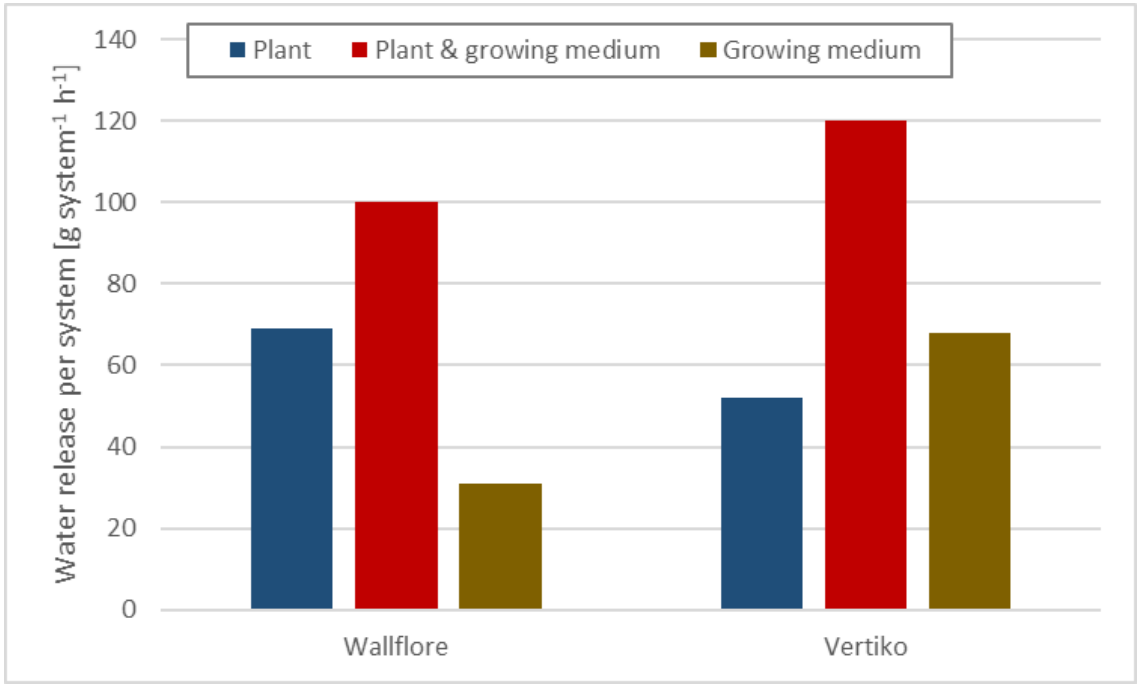
Factors influencing stomatal opening and transpiration

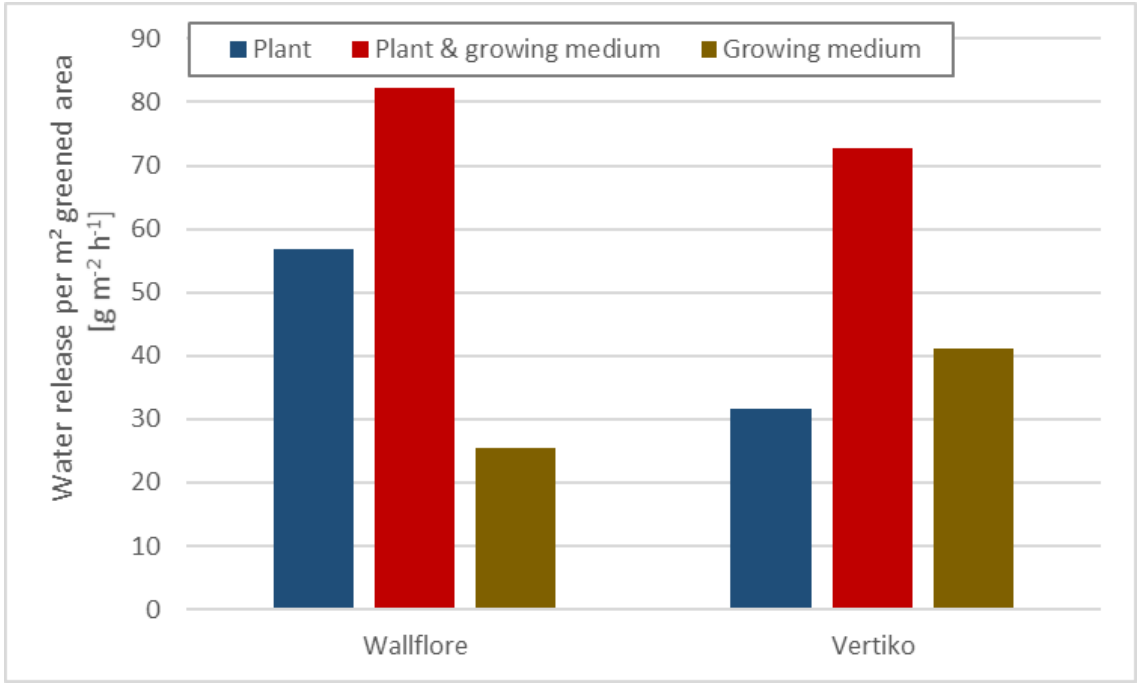
- Summary -

- Plant species → differences in stomatal opening and transpiration
- Increasing light intensity → enhances stomatal opening and transpiration
- Increasing relative humidity → increases stomatal conductance but not transpiration
- Increasing temperature → decreases stomatal conductance and transpiration
- Season → higher stomatal opening and transpiration in summer
- Growing media moisture → no influence

Results

Estimation of the contribution of transpiration to Evapotranspiration



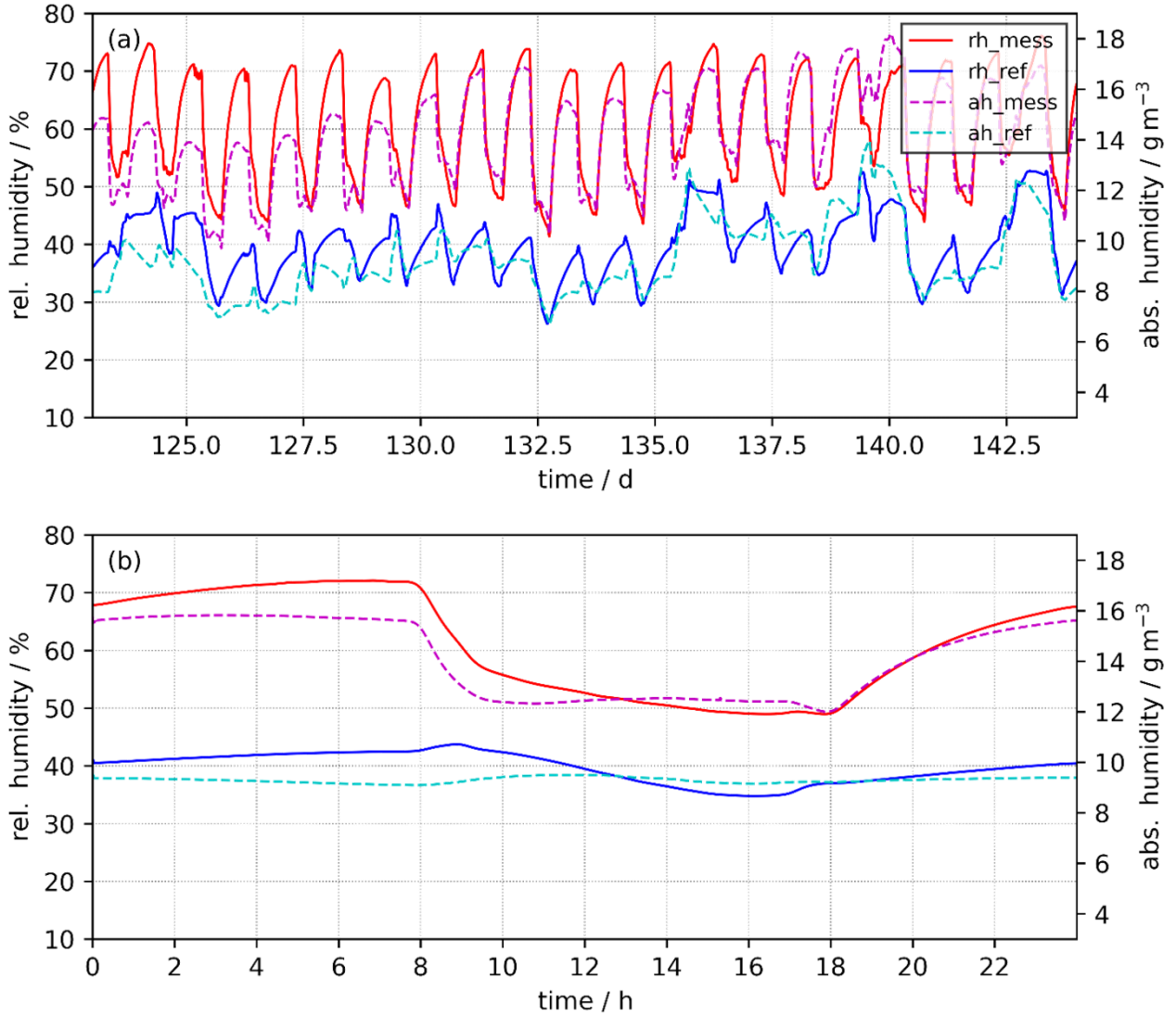


Transpiration rate of *Philodendron hederaceum* 'Brasil' compared with measured evapotranspiration rate of the greening system and calculated evaporation rate of the growing media at 45 % RH and 90 µmol m^{-2} s^{-1} PAR.
Based on a system leaf area of 1,92 m² for Wallflore and 1,44 m² for Vertiko (left) and additionally standardized to m² of greened area (right).

Results

Comparison of the air humidity in the measurement and reference room with the Wallflore system

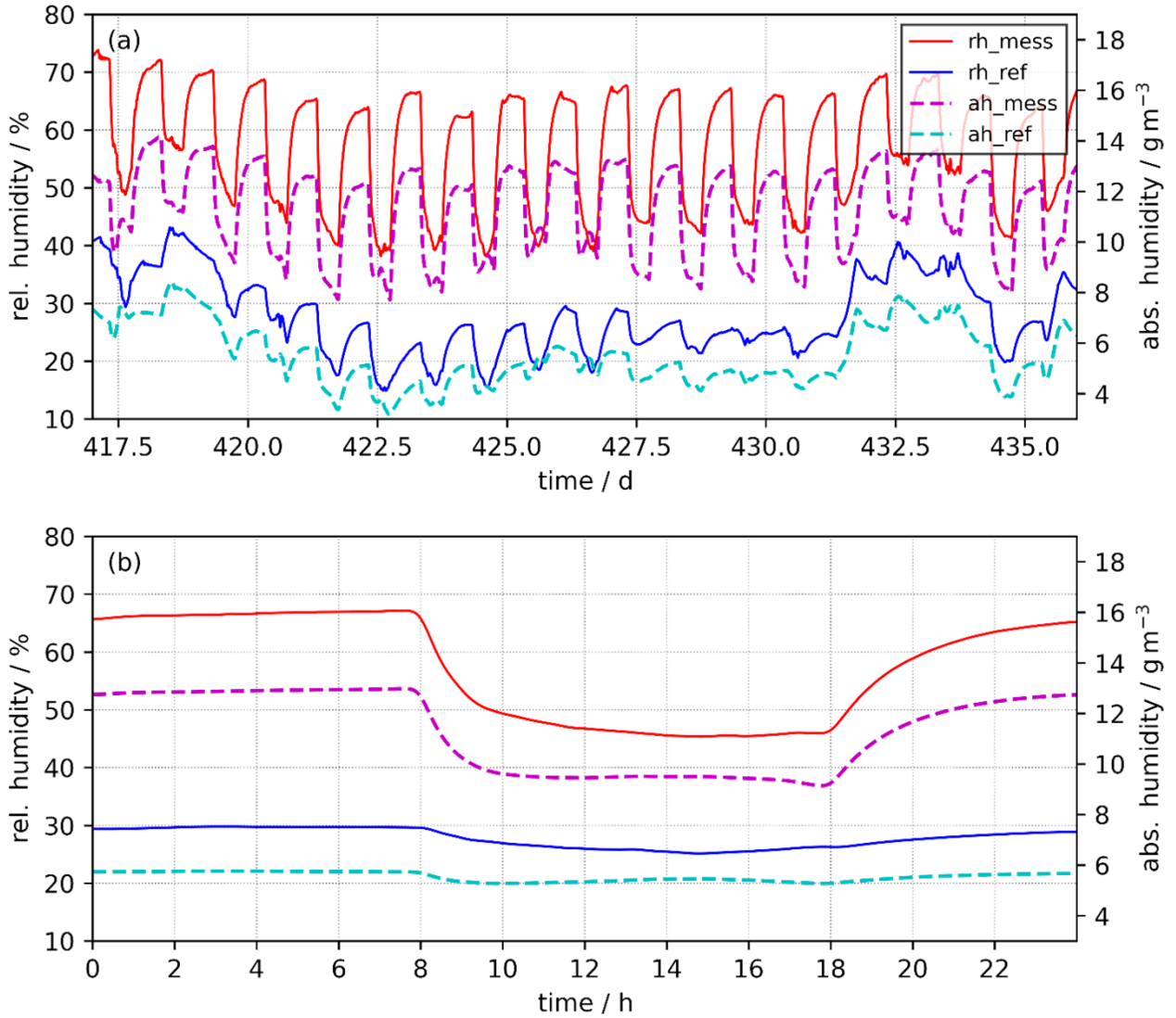
- Relative humidity (left axis, red and blue)
- Absolute humidity (right axis, magenta and cyan)
- **(a)** calendar day 123 (Tuesday, May 03rd) to 143 (Monday, May 21st) 2022
- **(b)** calculated mean value over the day



Results

Comparison of the air humidity in the measurement and reference room with the Vertiko system

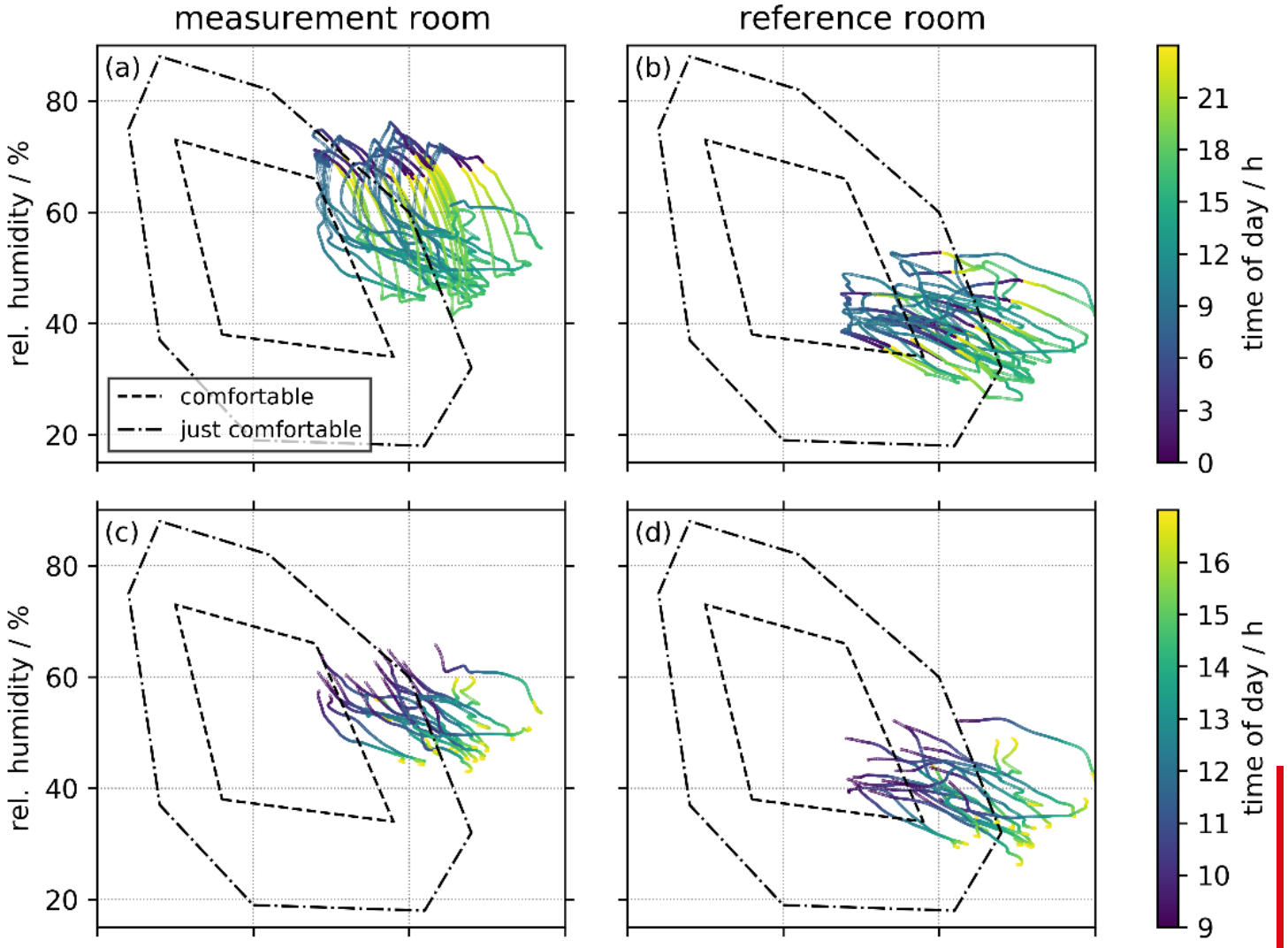
- Relative humidity (left axis, red and blue)
- Absolute humidity (right axis, magenta and cyan)
- **(a)** calendar day 417 (Wednesday, Feb. 22nd) to 436 (Monday, March 13th) 2023
- **(b)** calculated mean value over the day



Results

Comfort with vertical greening of the Wallflore system

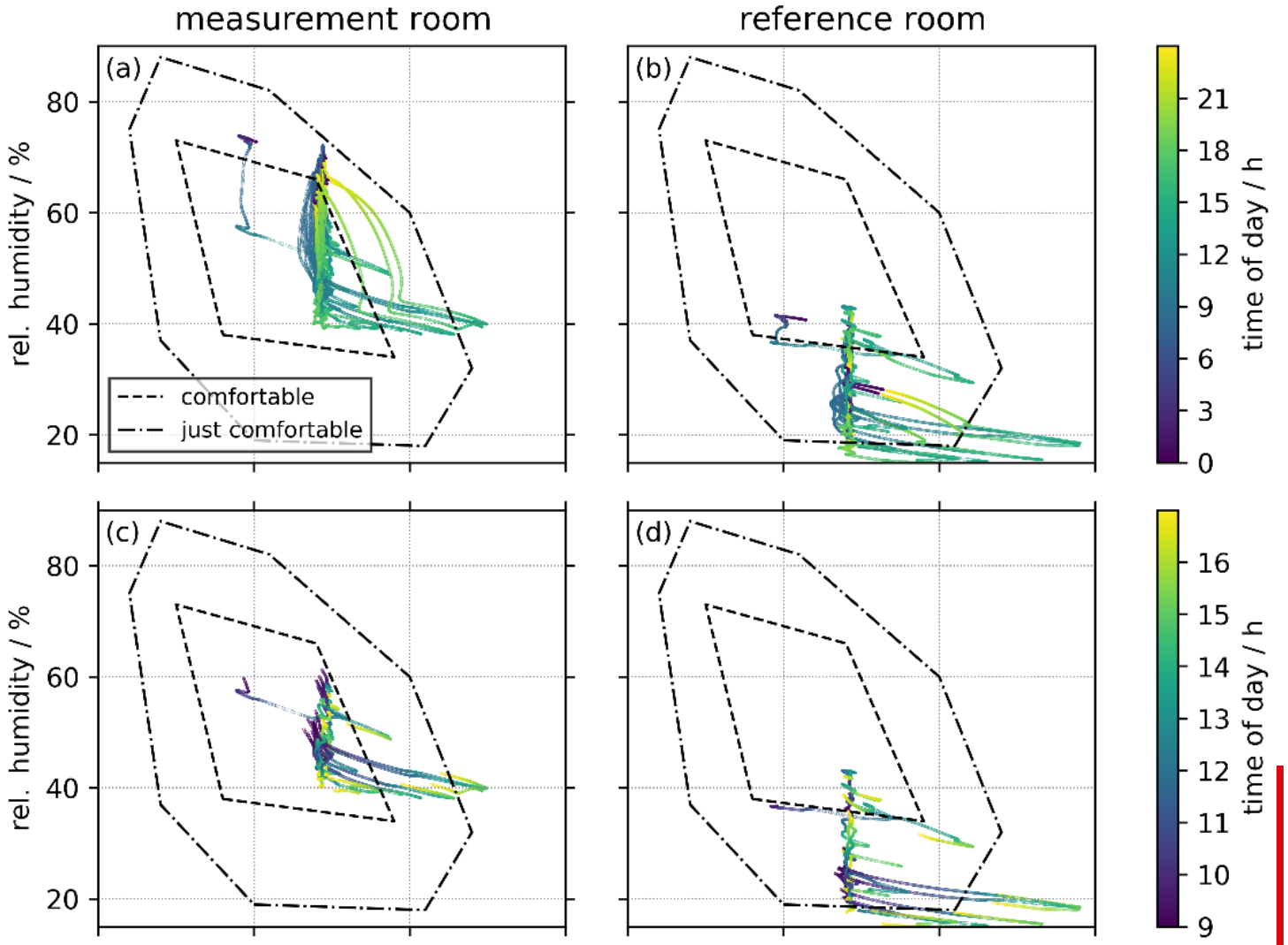
- Measurement room, graphs (a), (c), left
- Reference room, graphs (b), (d), right
- (a) and (b) entire evaluation period
- (c) and (d) only from 9 am to 5 pm
- Temperature is the mean value of the air temperature
- Evaluation period from Tuesday, May 03rd to Monday, May 21st 2022



Results

Comfort with vertical greening of the Vertiko system

- Measurement room, graphs (a), (c), left
- Reference room, graphs (b), (d), right
- (a) and (b) entire evaluation period
- (c) and (d) only from 9 am to 5 pm
- Evaluation period from Wednesday, February 22nd 2023 to Sunday, March 12th 2023



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- **SUMMARY AND OUTLOOK**

Summary

- Wallflore system
  - total cooling heat of about 16 kWh
  - average cooling capacity of around 35 W
- Vertiko system
  - total cooling energy of about 22 kWh
  - average cooling capacity of about 30 W
- Increased evaporation performance by a factor of about 1.5
- Regulation of the relative humidity in the room to about 50 % by varying the watering frequency
- Both greening systems result in keeping the indoor climate mostly in the "comfortable" temperature-humidity range during the day, while the ungreened reference room only achieves a "still comfortable"

Outlook

- Mapping in an app or connection to a smart home system are still pending
- Calculation of the greening effects on different buildings with a building simulation software
- Development and improvement of soil moisture sensors for regulation of indoor climate
- Development of the control strategy to optimise the transpiration performance based on the "Daily Light Integral"

***Philodendron hederaceum* `Brasil`**

Thank you for your attention

….and DBU for funding this project!

Dr. Michaela Reim
Center for Applied Energy Research e.V.
Magdalene-Schoch-Straße 3
97074 Würzburg
T + 49 (0) 931 70564-354
F + 49 (0) 931 70564-600
michaela.reim@cae-zerocarbon.de
www.cae-zerocarbon.de

Dr. Annette Bucher
University of Applied Sciences Weihenstephan-Triesdorf
Centre for Research and Knowledge Transfer, Institute of Horticulture
Am Staudengarten 8
85354 Freising
T + 49 (0) 8161 71-5620
annette.bucher@hswt.de
www.hswt.de

gefördert durch
Deutsche Bundesstiftung Umwelt
www.dbu.de