CELEBRATING 25 Years

THE UNIVERSITY OF ARIZONA
BIOSYSTEMS ENGINEERING
Controlled Environment Agriculture Center

Climate Control

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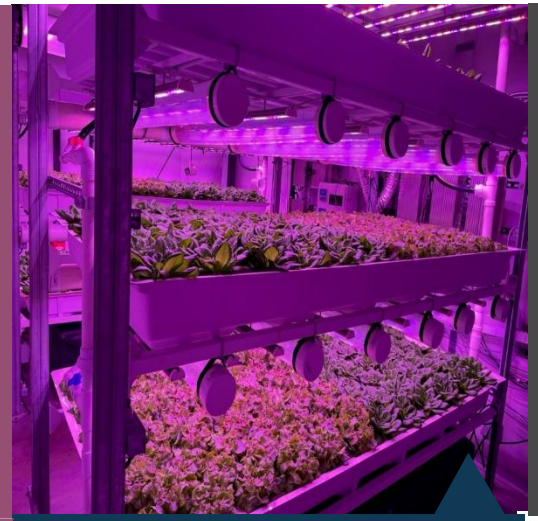
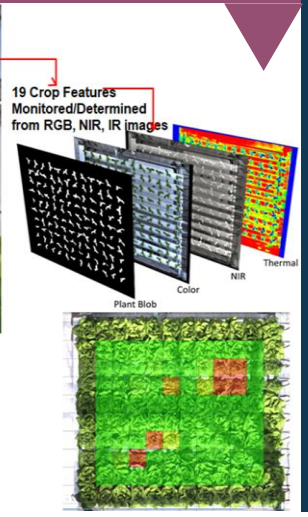
Kacira Lab Research emphasis

"precision agriculture applications in controlled environment agriculture systems (CEA) aiming to optimize resource use such as water, energy, and labor"

COMPUTER VISION

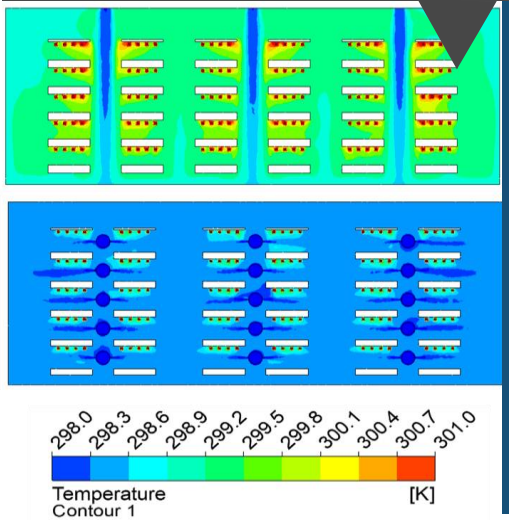
design, development and implementation of computer vision guided crop diagnostics and phenotyping systems for timely identification of crop status, stress locality for improved resource use efficiency





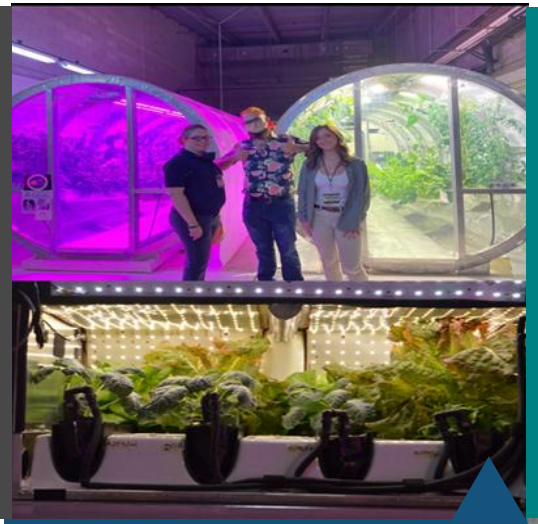
CLIMATE CONTROL

developing advanced climate control algorithms and strategies to optimize crop growing environments and resource use both in greenhouses and indoor vertical farming systems,



COMPUTATIONAL AERODYNAMICS

computational and experimental studies through aerodynamics analysis to improve climate uniformity and offer design recommendations for CEA systems



SPACE HORTICULTURE

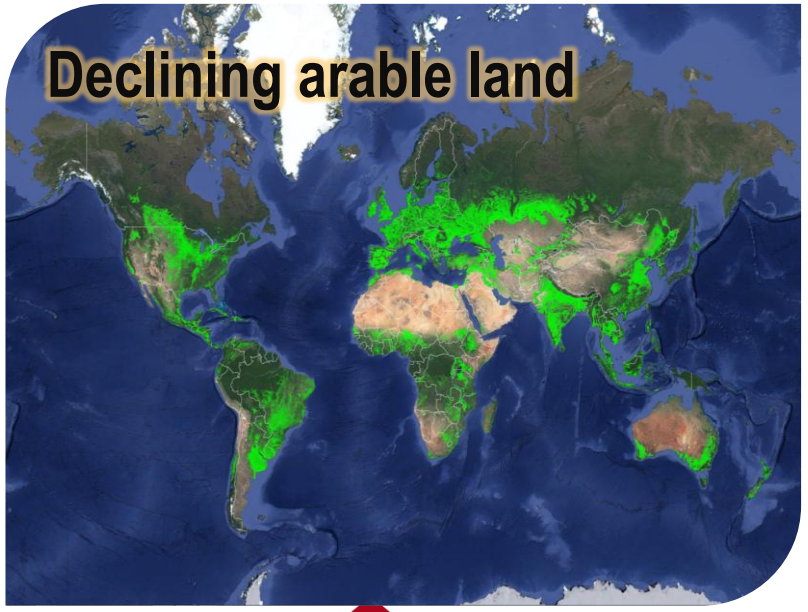
bioregenerative life support systems and crop production for space horticulture

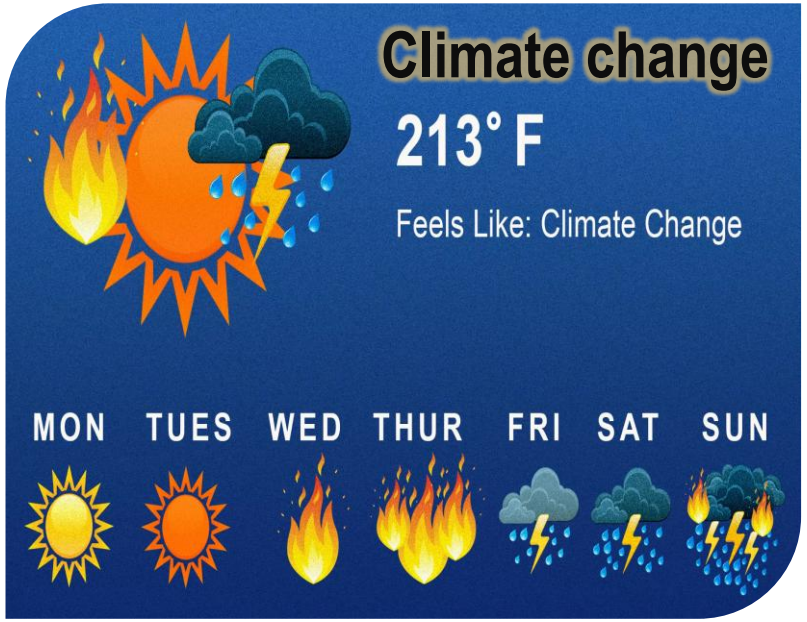
AGRIVOLTAICS & RENEWABLE ENERGY

alternative energy integrated energy electricity producing greenhouse systems

environmental control in microalgae production systems

Grand challenges



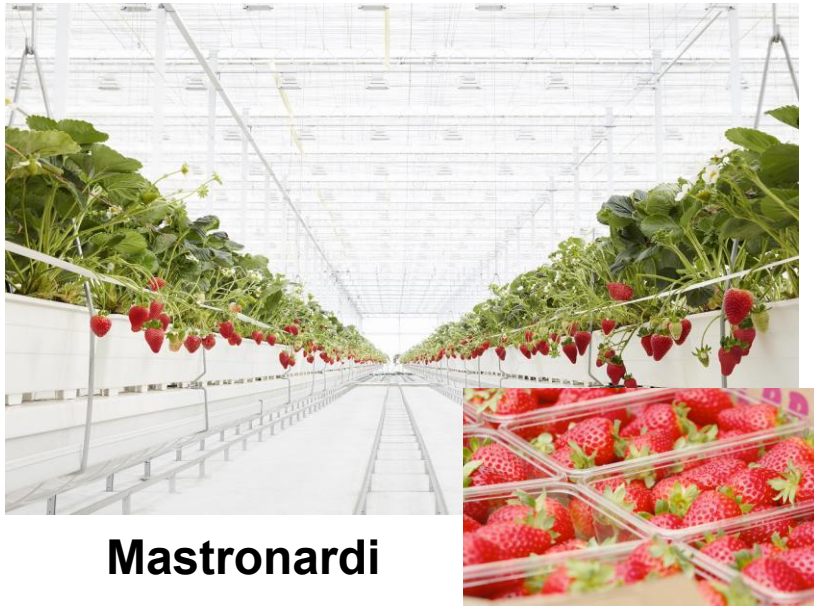


Integrated, Complementary, Smarter Production Agriculture Systems

Greenhouse technologies and industry are mature and advancing

Wholesum, AZ

Gotham Greens, CA/NY/IL/CO/TX



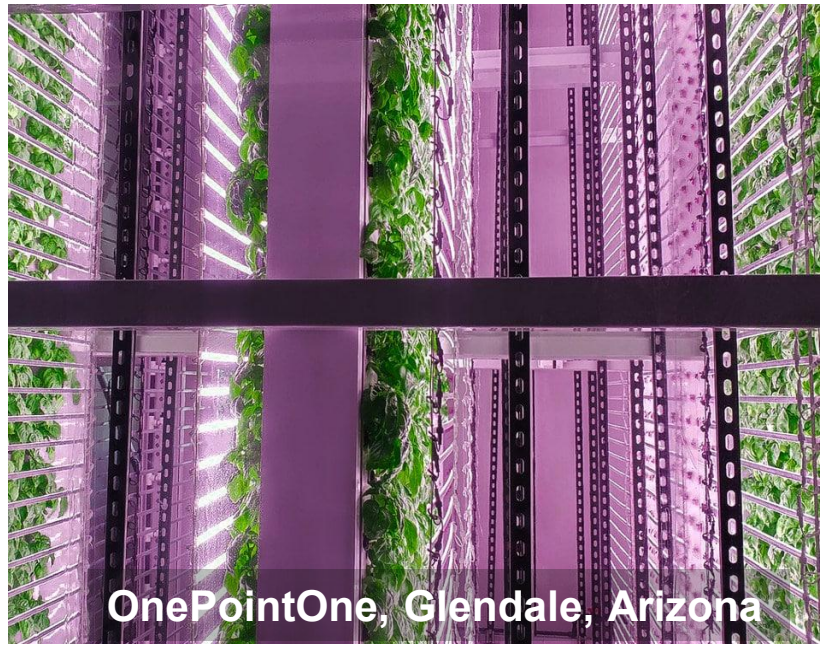
Mastronardi

Tanimura & Antle, TN

Winset Farms, CA

Bright Farms, PA/OH/NC/VA/IL

Adaptive Technology Levels for Controlled Environment Agriculture



Bottom Line! Maximize outputs while minimizing inputs *Resource use efficiency* (RUE)

"Maximize the plant growth with the minimum resource inputs, help contributing to minimum emission of environmental pollutants and minimum costs for the resources used"

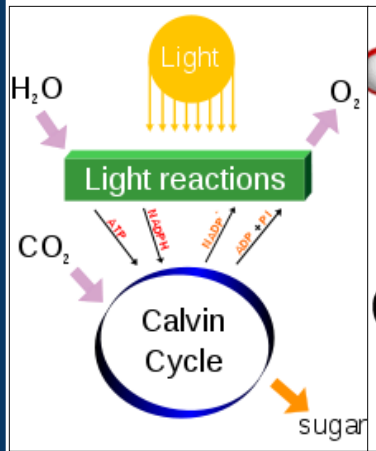
$$RUE = \frac{Crop Output\ (Yield)}{Resource\ Utilization}$$

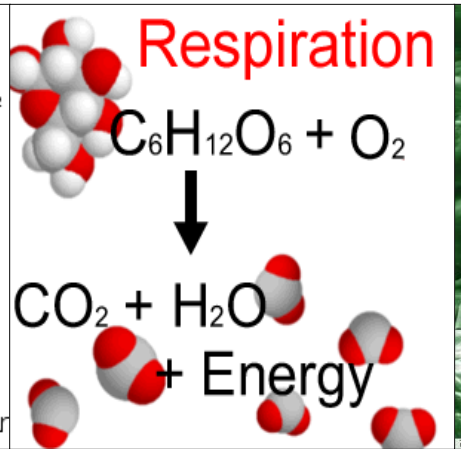
- Energy
- Water
- CO_2
- Fertilizer
- Labor

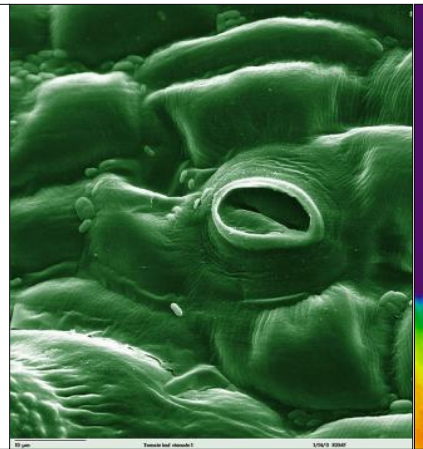
- Edible biomass
- Non-edible biomass
- Nutrients &water
- Transpired water vapor

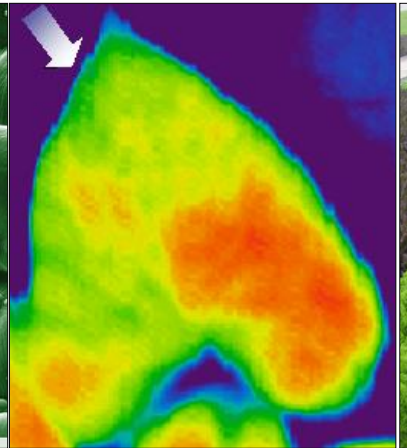
Crops are affected by surrounding microclimate in CEA systems

- Photosynthesis (Light energy → usable chemical energy)
- Respiration (Breaking Carbohydrates/fats → release CO_2, H_2O, Energy)
- Transpiration (Evaporation of water from plants)
- Leaf and fruit temperature
- Yield
- Quality

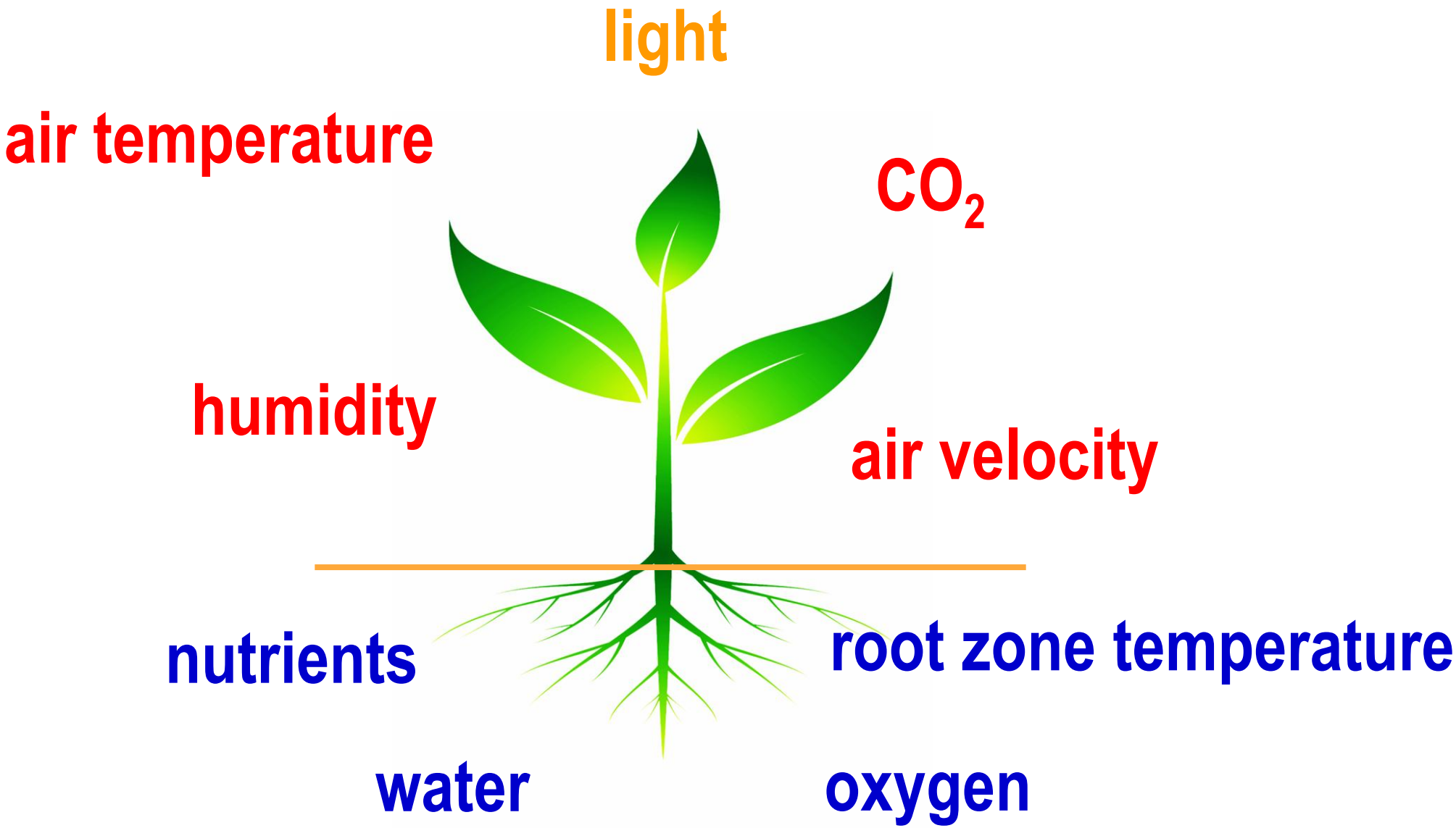








Nine significant parameters affecting plant growth

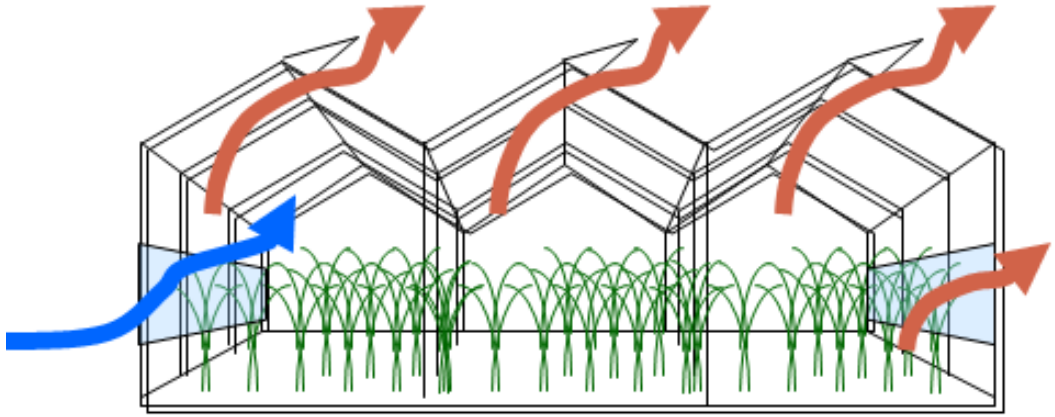


Environmental control in CEA

- Ventilation
- Air circulation and uniformity
- Cooling
- CO2 enrichment
- Heating
- Supplemental Lighting
- Humidification
- Climate control
- Dehumidification
- Trends and opportunities

Ventilation

- Exchange of air between Inside and outside of CEA system
- Initial stage of cooling
- Benefits
  - Temperature control
  - Remove moist air
  - Replenish CO2
  - Reduce thermal stress for workers
- Air exchange rate depends on:
  - Outside and inside climate
  - Cooling/heating equipment
- Methods
  - Mechanical ventilation
  - Natural ventilation

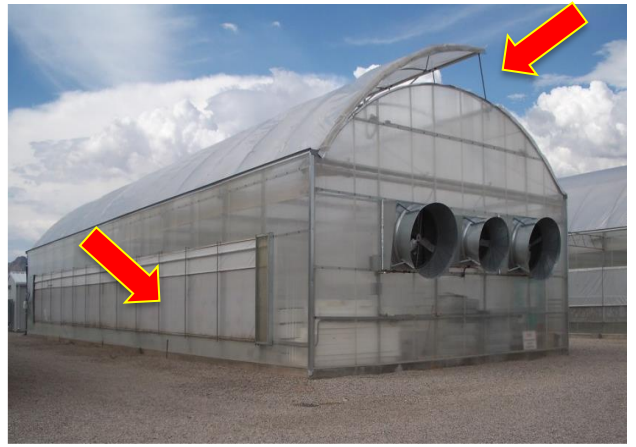


Mechanical Ventilation

- Actively produced by FANS other hardware to move air around
- Pressure driven air movement
- Use fan staging
  - Match cooling more precisely
  - Prevent over-cooling
  - Save energy
- Use variable speed fans
  - Limit ON/OFF cycling
  - Reduce wear and tear in mechanical systems
  - Save energy
- Fans deliver or extract air from vertical farms using diffusers at many locations

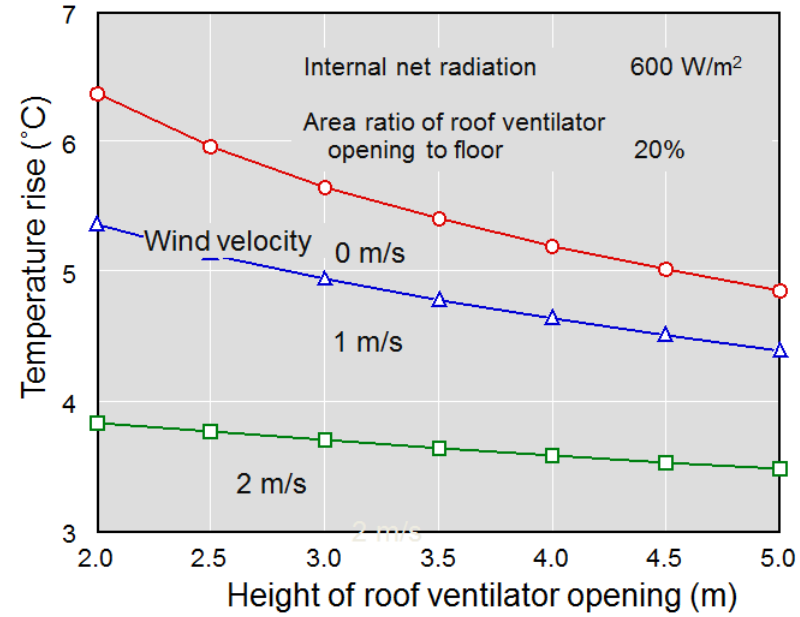
Natural Ventilation

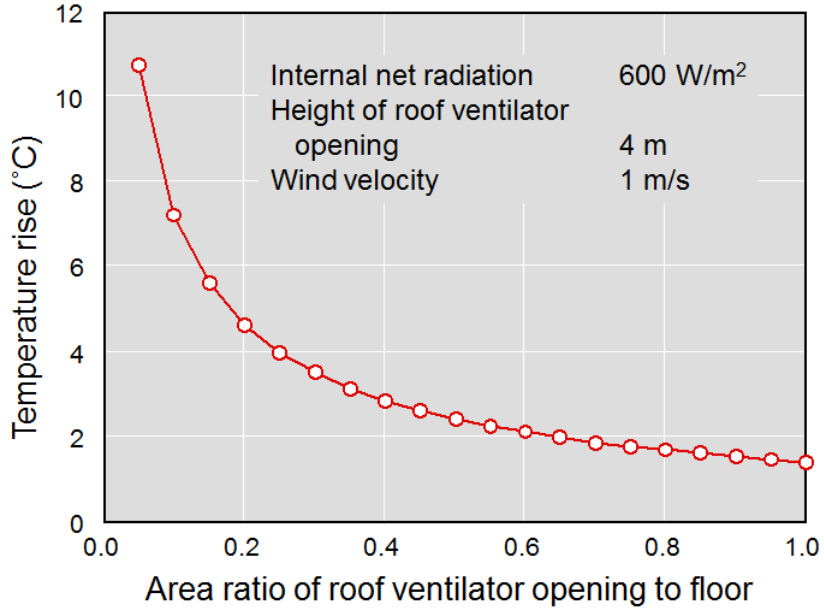
- *Passively* produced by VENTS/OPENINGS on roof and walls
- Air movement into and out greenhouse/vertical farm due by
  - Wind effect (due to pressure gradients)
  - Buoyancy/Chimney effect (due to air density change by temperature gradients)



Factors affecting natural ventilation in greenhouses

- Max. height between incoming air opening and outgoing air vent opening
- Total area of vent openings for incoming and outgoing air
  - Min. vent area/GH floor area w/o insect screens (≥ 40-45%)
- Taller greenhouse increase chimney effect





(S. Sase)

The effect of insect screens on ventilation

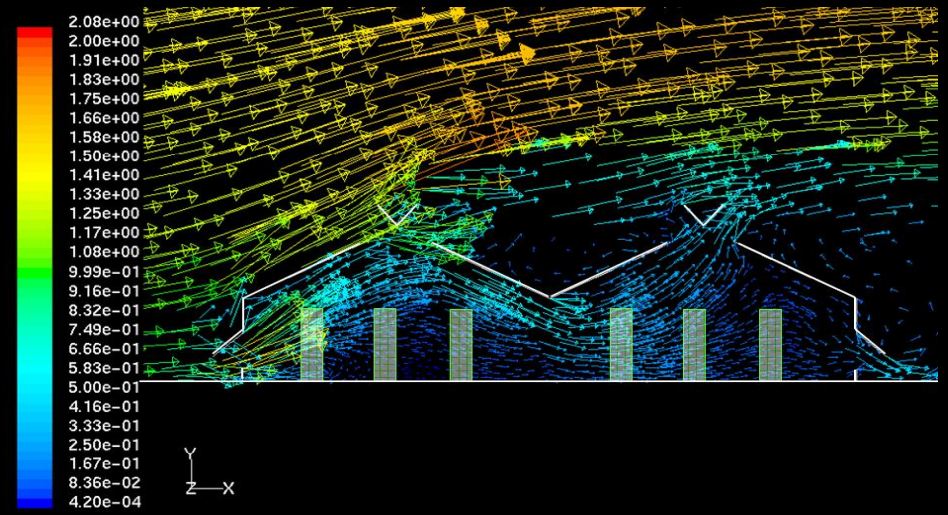
- Reduces insect migration and crop damage
- Reduced ventilation significantly due to resistance to air flow
- Increased internal air temperature
- Pay attention to dust accumulation
- Increase the ratio of opening to floor area (≥ 45-50%)

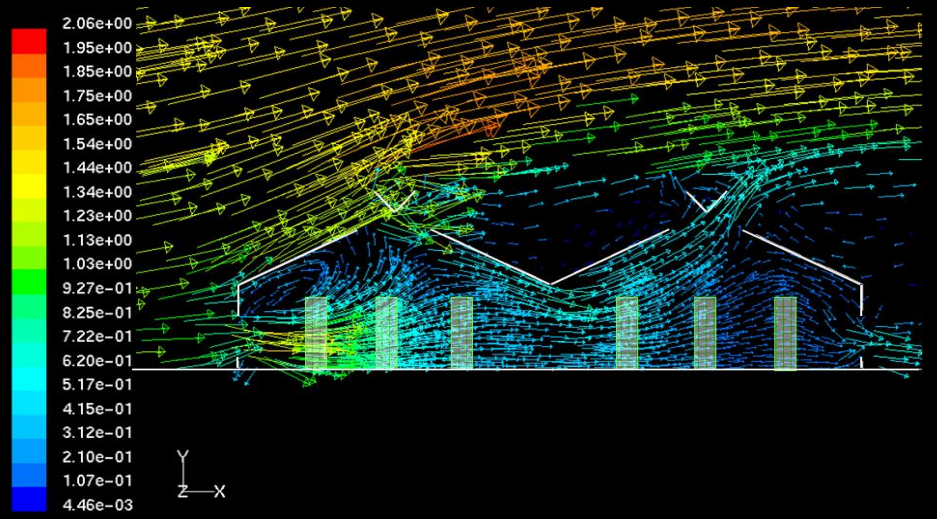

Image by M. Jensen

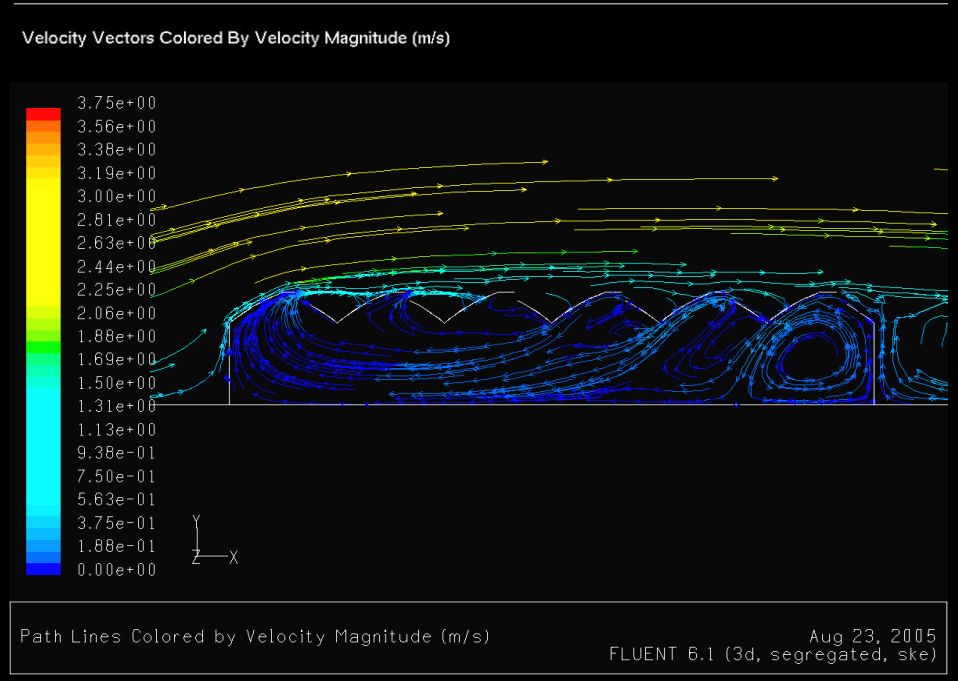

Image by M. Jensen

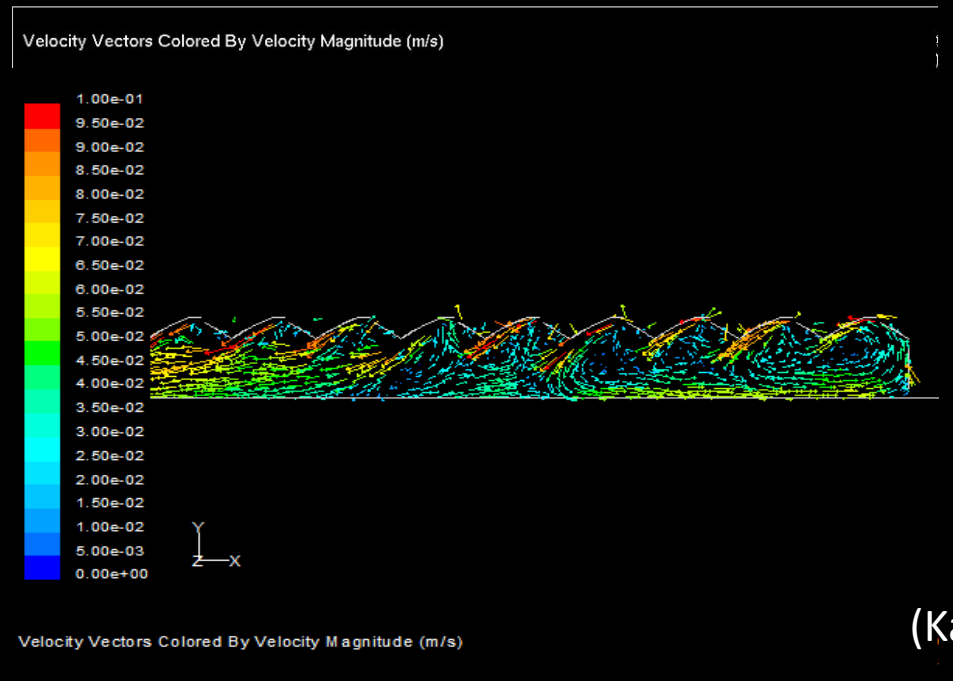
- Insect screen in vent openings may cause reduction on greenhouse ventilation Combined use of roof and side vents is recommended.

Effects of locations and directions of vent openings





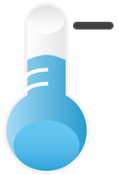




(Kacira 2005)

Mechanical vs Natural Ventilation

Mechanical Ventilation	Natural Ventilation
Advantages • Easy to design and control • Easy to measure • Predictable (vent rates and flow direction are known) • Use with wet pad, fogging and misting	**Advantages** • Uniformity achieved especially when roof vents are used and properly designed • Lower energy use to open/close vents • Use with fogging or mist evaporative cooling • Cheaper to operate • More affective when outdoor temp is lower
Disadvantages • Airflow in one direction • Produces non-uniform conditions • Use more energy to operate	**Disadvantages** • Difficult to control vent rates • At the mercy of outside conditions • Difficult to predict/measure vent rates • Vent rates can be very low or very high!



Cooling

Reduce indoor air temperature by removing heat energy in the growing space

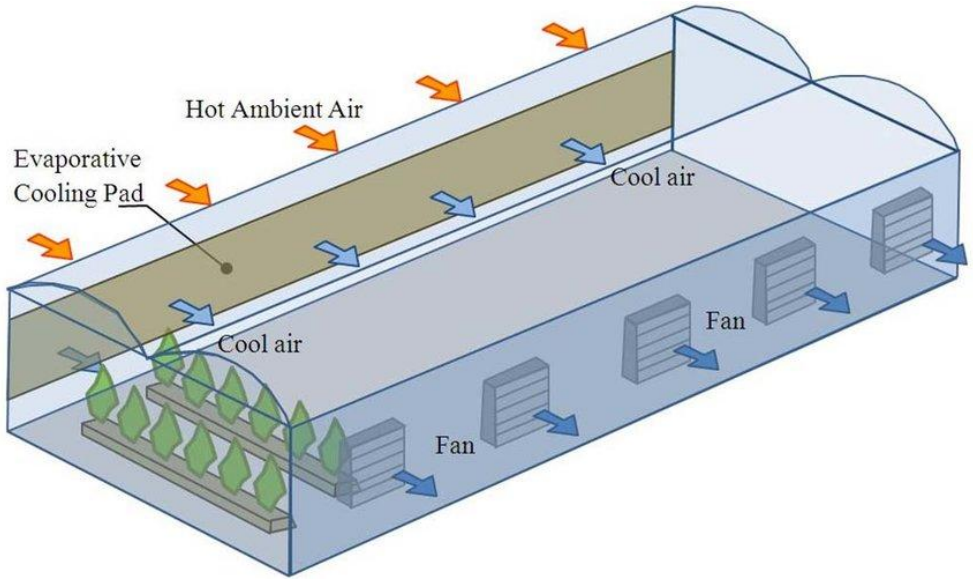
- Evaporative Cooling (transferring heat to water)
  - Wet Pad & Fan
  - High pressure fogging
  - Low Pressure mist
- Refrigerant based cooling (transferring heat to refrigerant)
- Shading (Block irradiance from entering greenhouse to cause heat build-up)
- White-wash

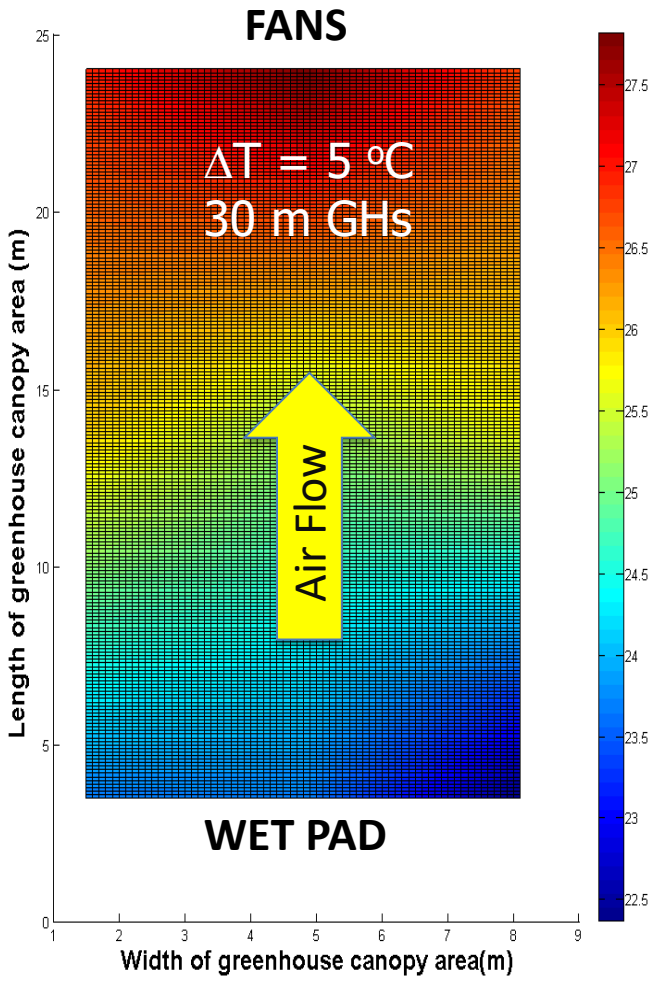
Evaporative Cooling

- Cooling with humidification
- Effective in hot and dry climates
- Less effective in hot and humid climates
- Methods
  - Wet Pad & Fan
  - High pressure fogging
  - Low Pressure mist

Wet Pad and Fan Evaporative Cooling

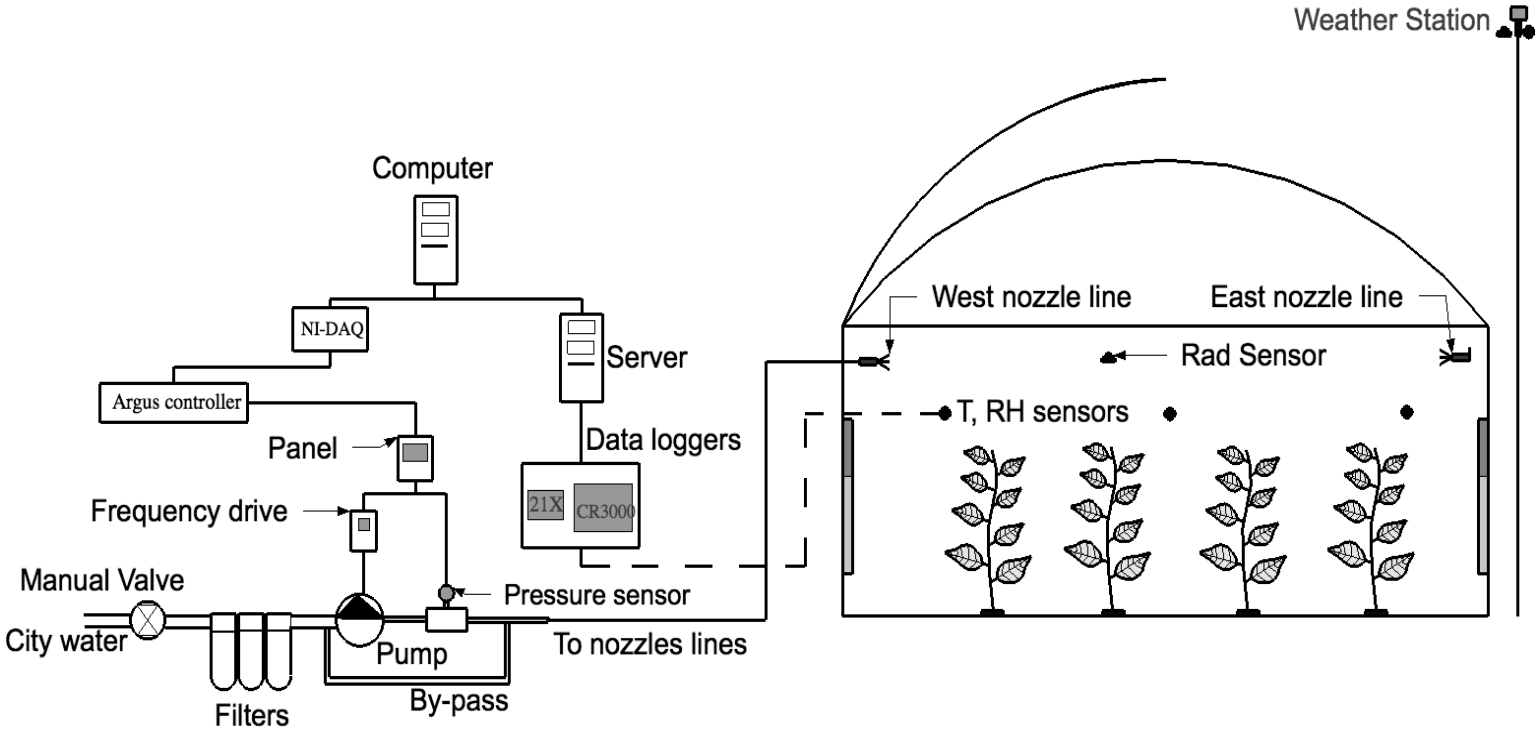
- Water in wet pad absorbs sensible heat form air
- Air temp ↓ RH ↑
- Warm and humid air exits from exhaust fans
- Non-uniform environment





High Pressure Fogging or Misting

Humidification



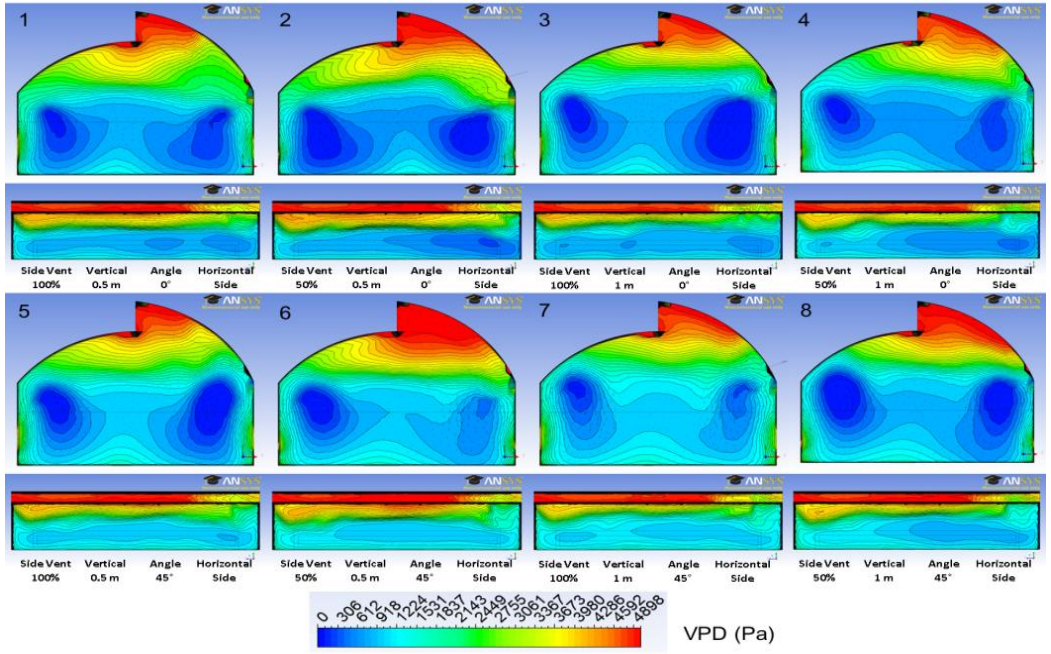
Misting and High-Pressure Fogging

- Low-pressure misting
  - Large nozzle orifices (holes)
  - Working pressure < 0.4 MPa (50 psi)
  - Large water droplets (> 100 μm = 0.1 mm)
  - *slow evaporation mostly on crop and ground surfaces*

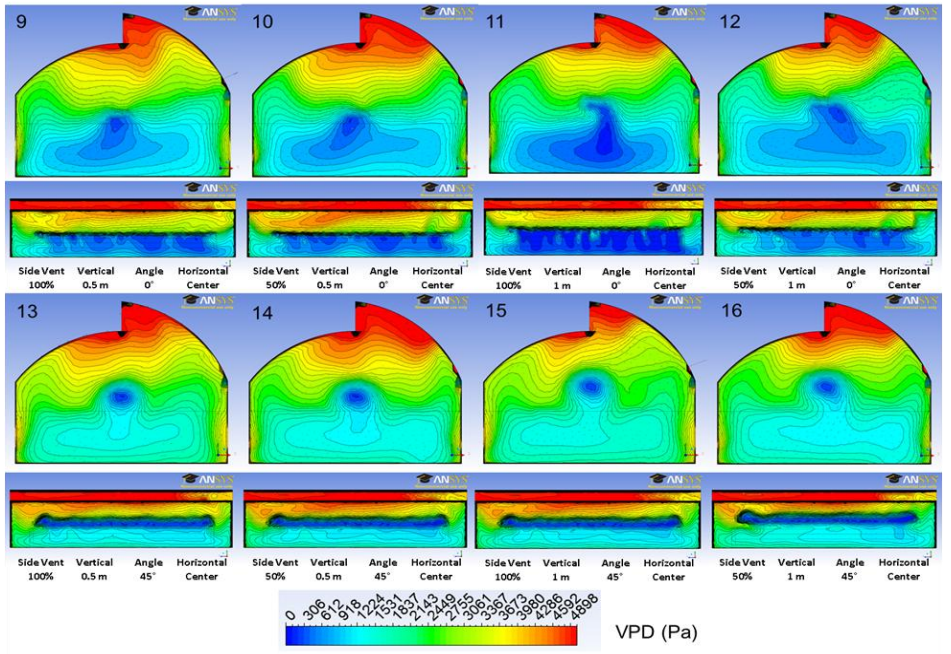
- High-pressure fogging
  - Small nozzle orifices (holes)
  - Working Pressure = 7-14 MPa (1000-2000 psi)
  - Very small water droplets (5-20 μm)
  - *fast evaporation of water…in the air!*

Greenhouse climate uniformity under natural ventilation with high pressure fogging using Computational Fluid Dynamics (CFD) simulation (Tamimi and Kacira, 2013)

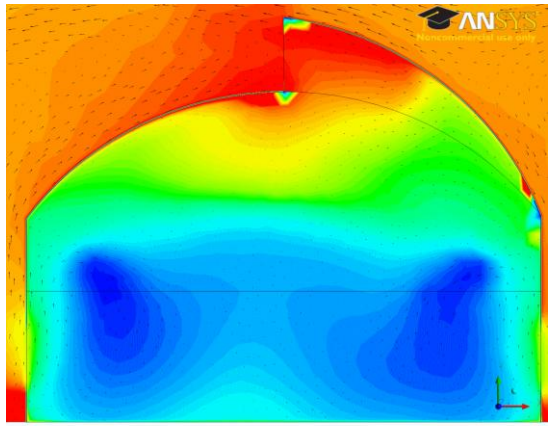
Fogging nozzles on sides

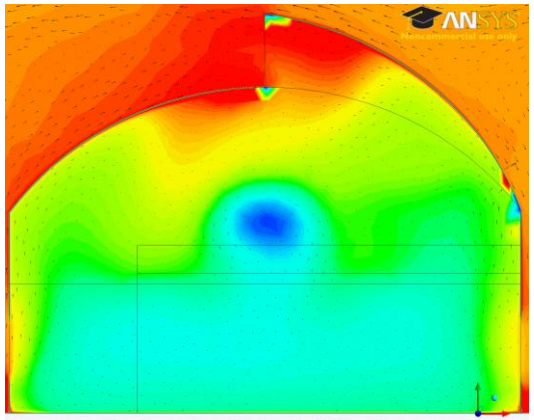


Fogging nozzles at center

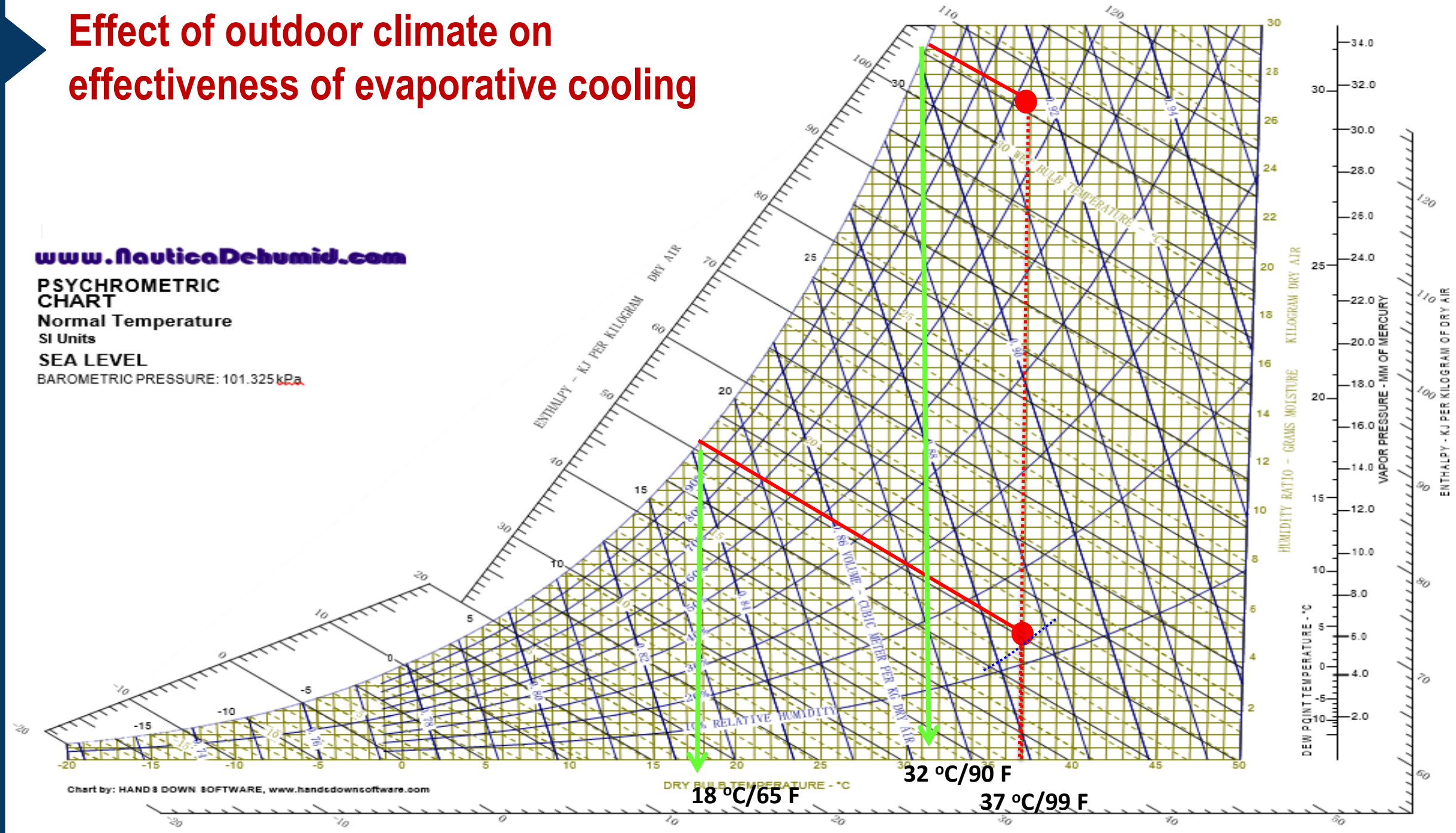


- Direct fog into air stream/flow
- The higher the nozzle position the better → minimize water on plants (try 1 m distance from nozzle to plant)



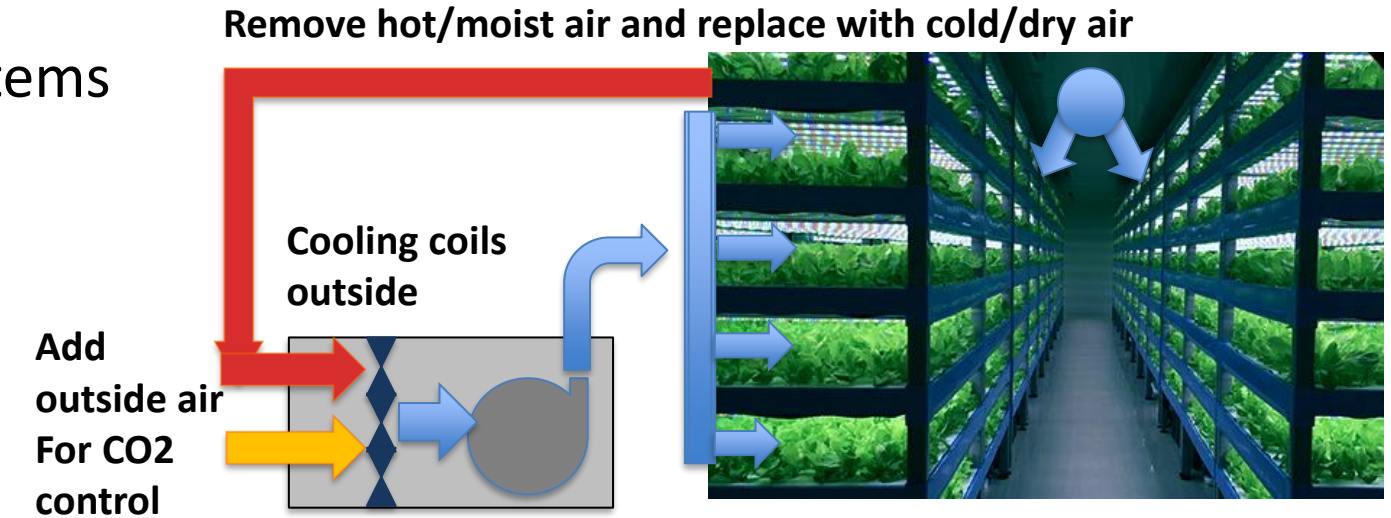


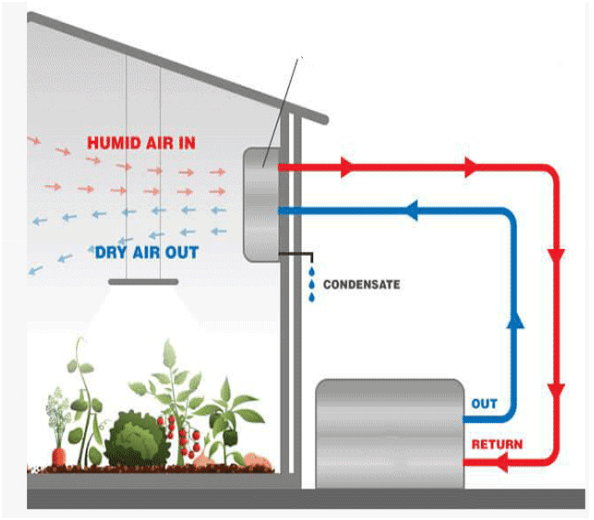
Effect of outdoor climate on effectiveness of evaporative cooling



Refrigeration based Cooling

- Simultaneous cooling and dehumidification
  - Most effective in hot, humid climates
- Closed/semi-closed environments (vertical farms)
- Common Systems
  - Ducted
  - Split Systems





Shading and White-Wash based Cooling

Energy Producing Greenhouse Systems

(Kacira et al., 2012-2022)

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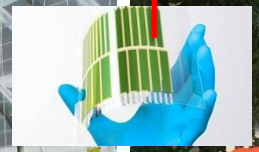
ABENGOA
ABENGOA SOLAR



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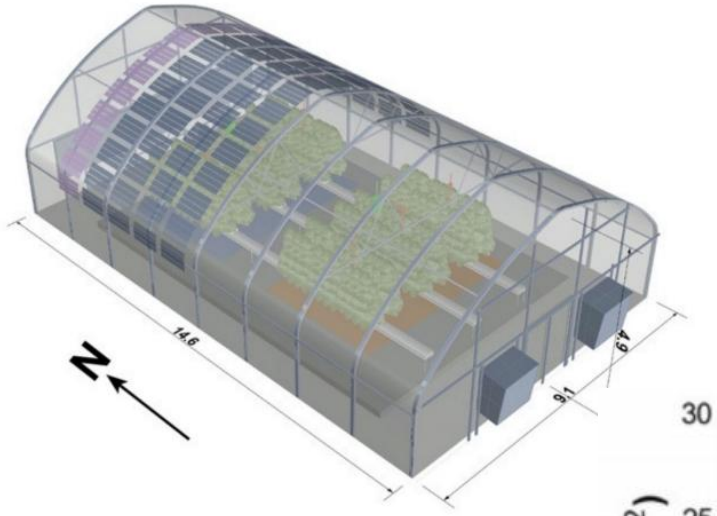
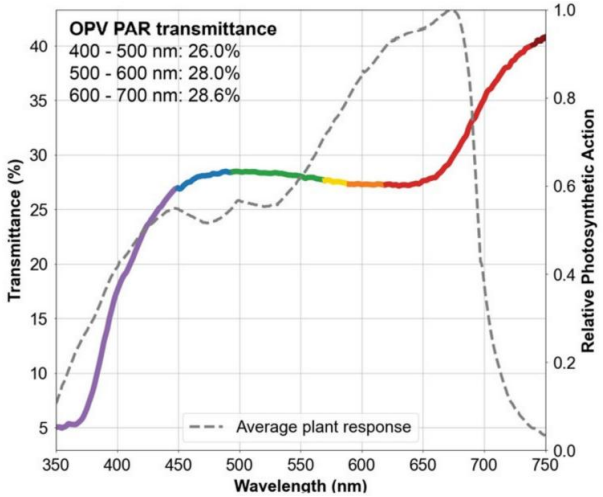
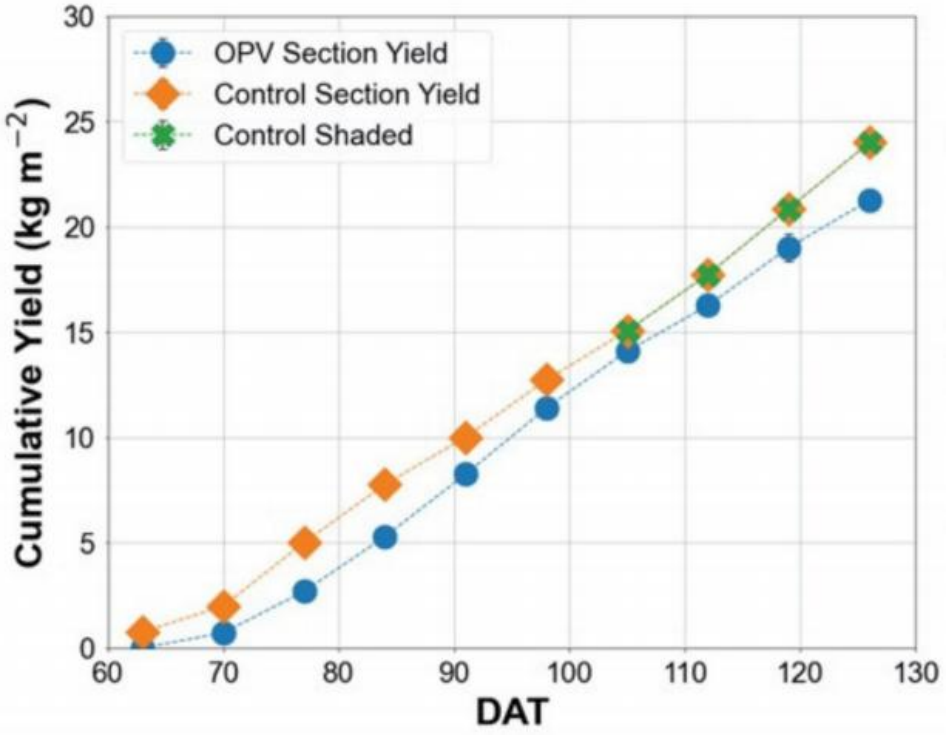
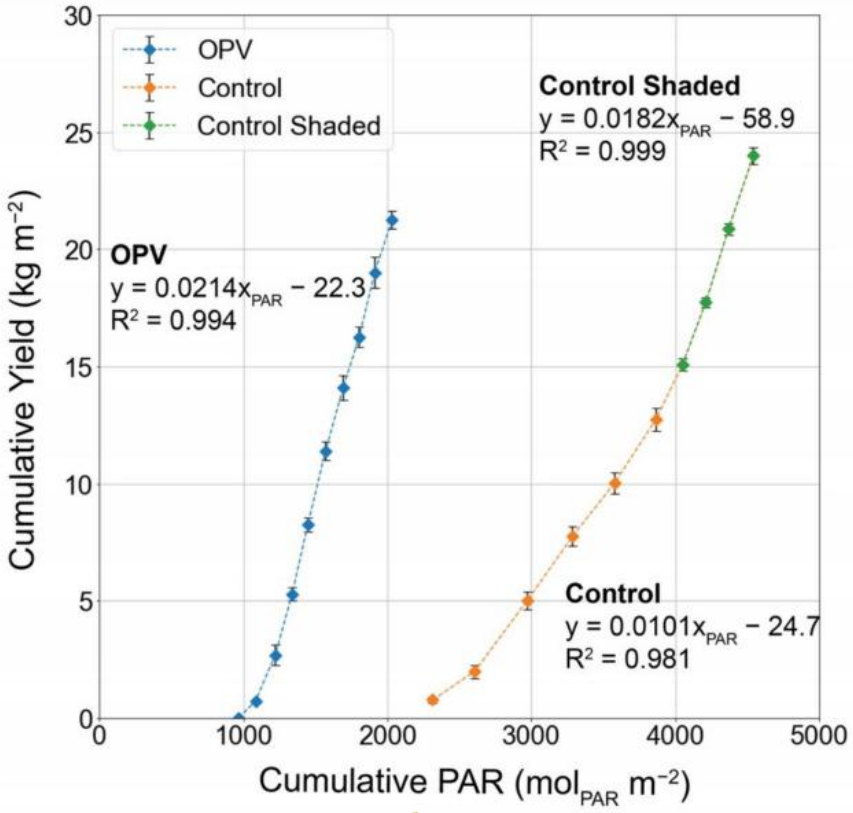
Semi-Transparent Organic Photovoltaics Applied as Greenhouse Shade for Tomato Production in Arid Climate

Bekah Waller, PhD 2021









BARD

NSF

Grodan

Wavelength selective greenhouse covering

(UArizona: Kacira, T. Mahato, B. Blue; RedSea: R. Lefers, M. Tester, 2024)

REDSEA

Control

NIR filtered

Heating

- Increase air temperature in the growing space
  - Add heat energy to grow space
- Reduce relative humidity, but not water vapor content
- Common methods

a) Hot Air: Add heat to air directly

b) Hot Water: Heated water to pipes, radiators, and heat exchangers

c) Radiant: Emit heat to crop leaves/canopy

d) Refrigerant: Heat pump

Hot air and Hot water Heating

Hot Air

Advantages

- Can combine w/heat recovery
- Can use off-gas for CO_2 enrichment

Disadvantages

- Non-ducted: Poor circulation
- Non-ducted: Off-gas from indoor furnace contains ethylene and CO
- Ducted: Reduce light transmission in greenhouse
- Ducted: Fan energy required to distribute hot air uniformly

Hot Water

Advantages

- Can use solar thermal, geothermal, heat recovery
- Heat delivery closer to plants
- More energy efficient to “move” water than air

Disadvantages

- Hot pipes near work zone
- Perimeter heating is far from plants
- More complicated to design and install

Refrigerant and Radiant based Heating

Refrigerant

Advantages

- Can be used for cooling as well
- Good uniformity if many indoor units used
- High energy efficiency

Disadvantages

- Overhead/wall units reduce light transmission to crop
- Need many indoor units to achieve uniformity
- Need high energy input

Radiant

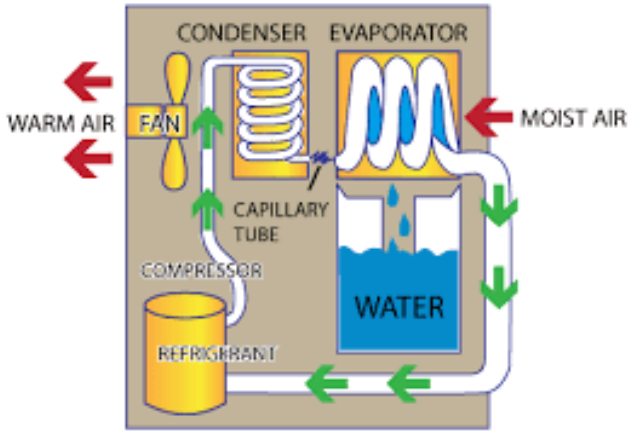
Advantages

- No need for air movement for distribution
- Emits heat directly to crop surfaces

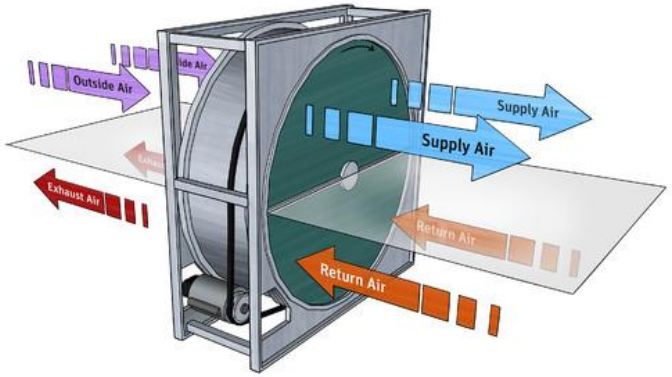
Disadvantages

- Inefficient use of electricity
- Overhead units reduce light transmission
- Need many radiators to achieve uniformity

Dehumidification



- Remove moisture from crop growir space
- Best applications
  - Humid climates (hot or cold)
  - Mold control
  - Humidity control is significant
- Primary methods
  - a) Direct Expansion cooling
  - b) Desiccant wheels
  - c) Salt-Brine



Dehumidification

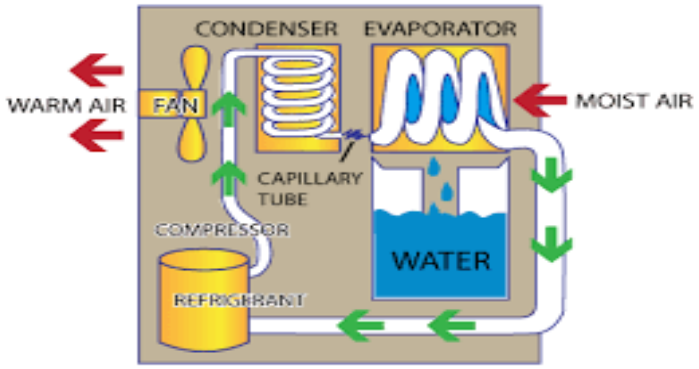
Direct Expansion/Cooling Coil

Advantages

- Can cool simultaneously
- Best in hot, humid climates and Vertical Farms
- Can collect and reuse condensate

Disadvantages

- Cooling and dehumidification don't always match
  →may need to reheat or re-humidify
- Requires large volumes of air to be circulated
- Energy Intensive: Large energy use by compressors and fans



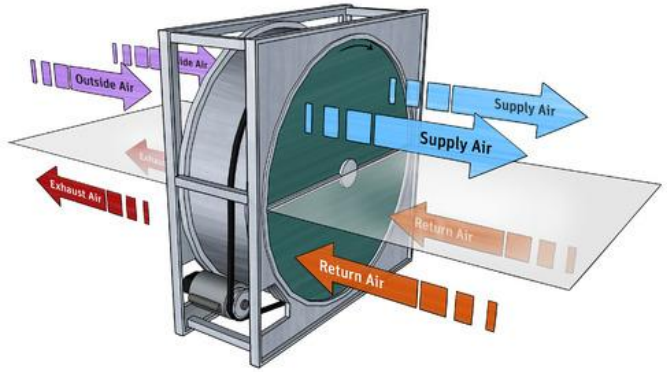
Desiccant, Salt-Brine

Advantages

- Can simultaneously heat
- Best in cold, dry climates
- Heat production generally cheaper than electricity

Disadvantages

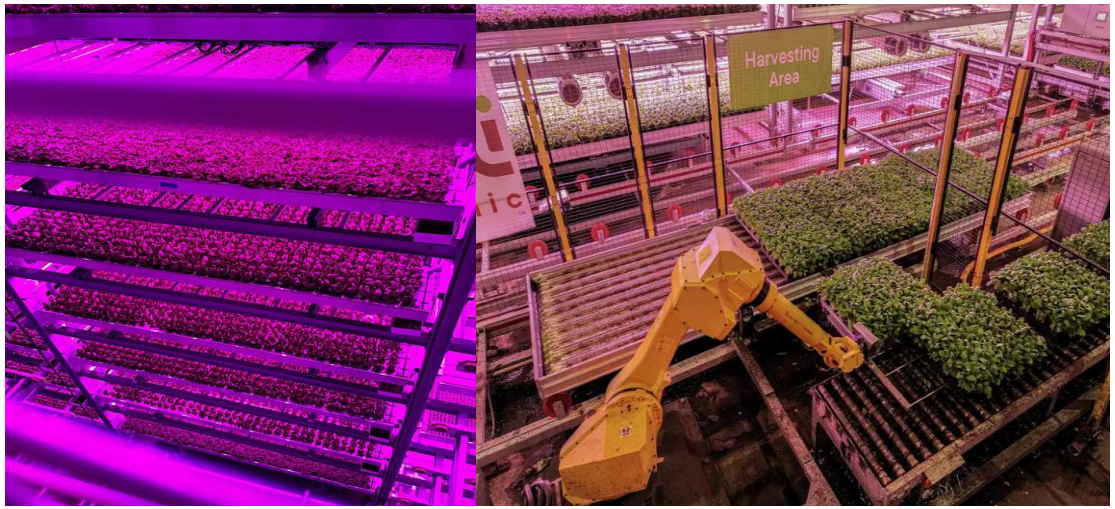
- Cannot collect and reuse condensate
- Heating and dehumidification don't always match
  →may need to re-cool or re-humidify



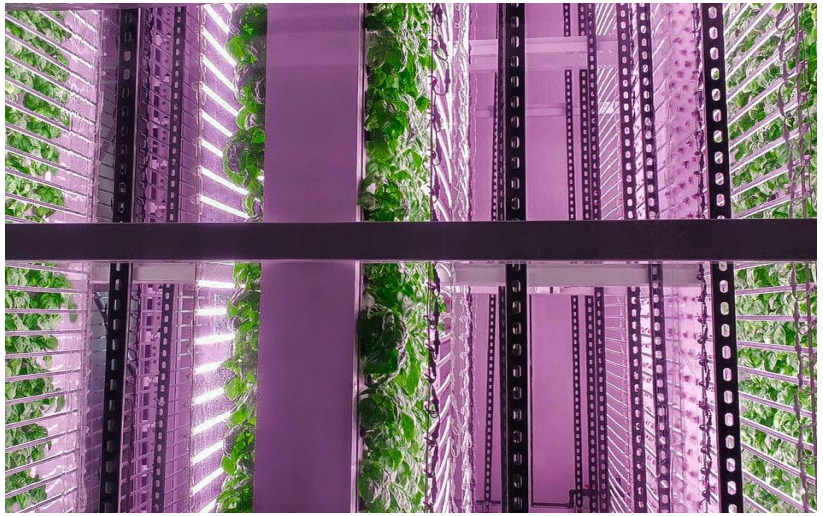
Air Circulation and Uniformity

- Air movement
  - Enhance gas exchange
  - Prevent condensation on crop
- Methods
  - Horizontal Air Flow (HAF fans)
    - Desired air speed 0.25 - 0.50 m/s
    - Need about 0.65 - 0.95 m^3/min per m^2 floor area
    - 30 -50 cm fan blade diameters with guards
  - Vertical Air Flow
  - Air diffusers/Ducted systems

Vertical Farming has been evolving



80 Acres Farm/SoliOrganics, OH, VA, TX



OnePointOne, Glendale, Arizona

Plenty, CA, VA

AeroFarms, NY, VA, UAE

Warehouse Based Vertical Farms

AeroFarms, New Jersey, USA

Plenty, San Francisco, CA, USA

OasisBiotech, NV, USA

JPFA, Chiba, Japan

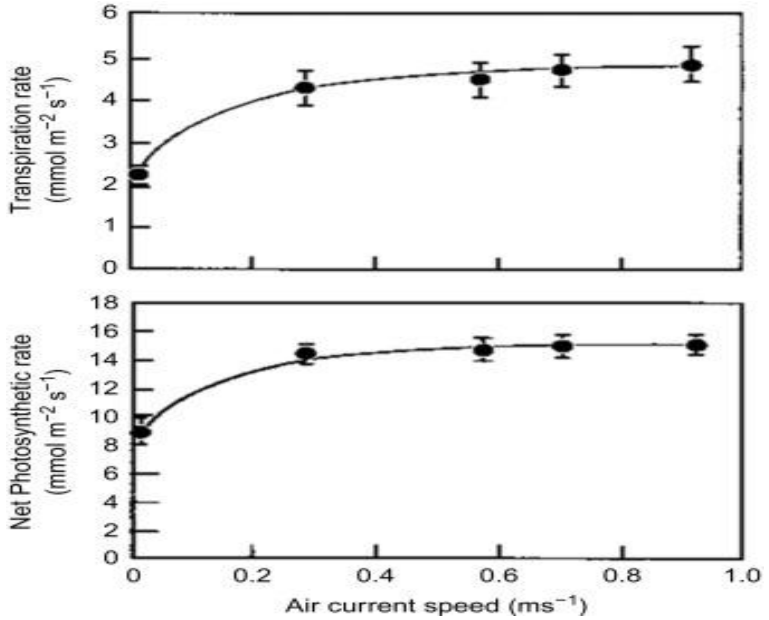
Shenandoah Growers, VA, USA

Farminova, Antalya, Turkey

Effects of inadequate and non-uniform air flow in vertical farms

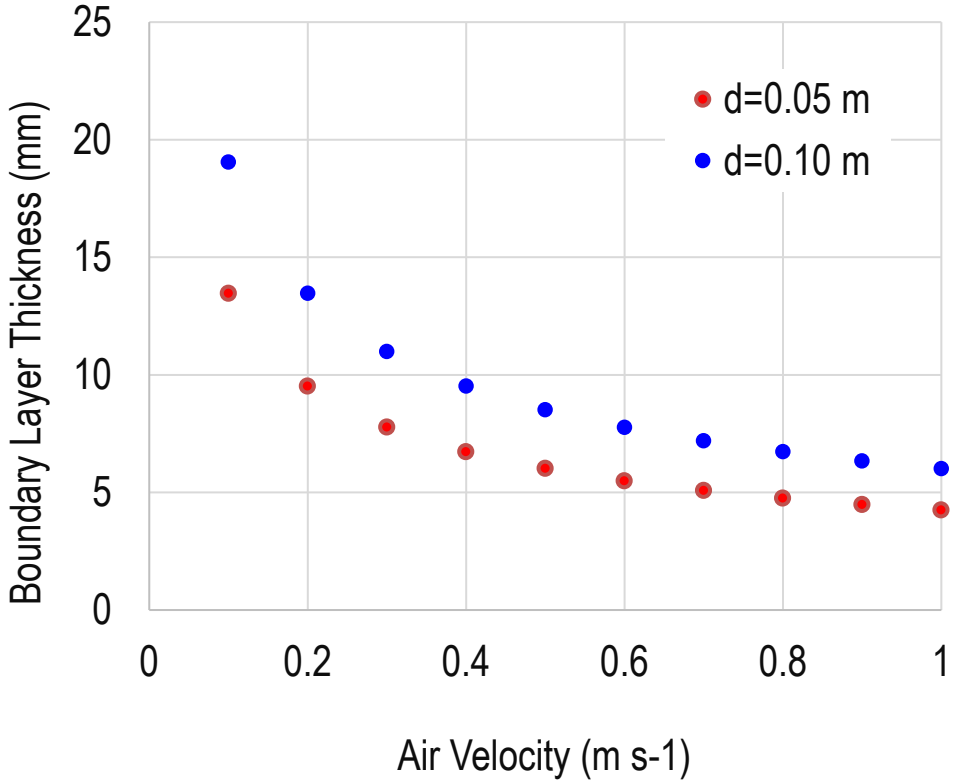
- **Stagnant boundary layer**
- **Photosynthesis and transpiration rate**
    - Potential crop disorders: e.g. tipburn of lettuces

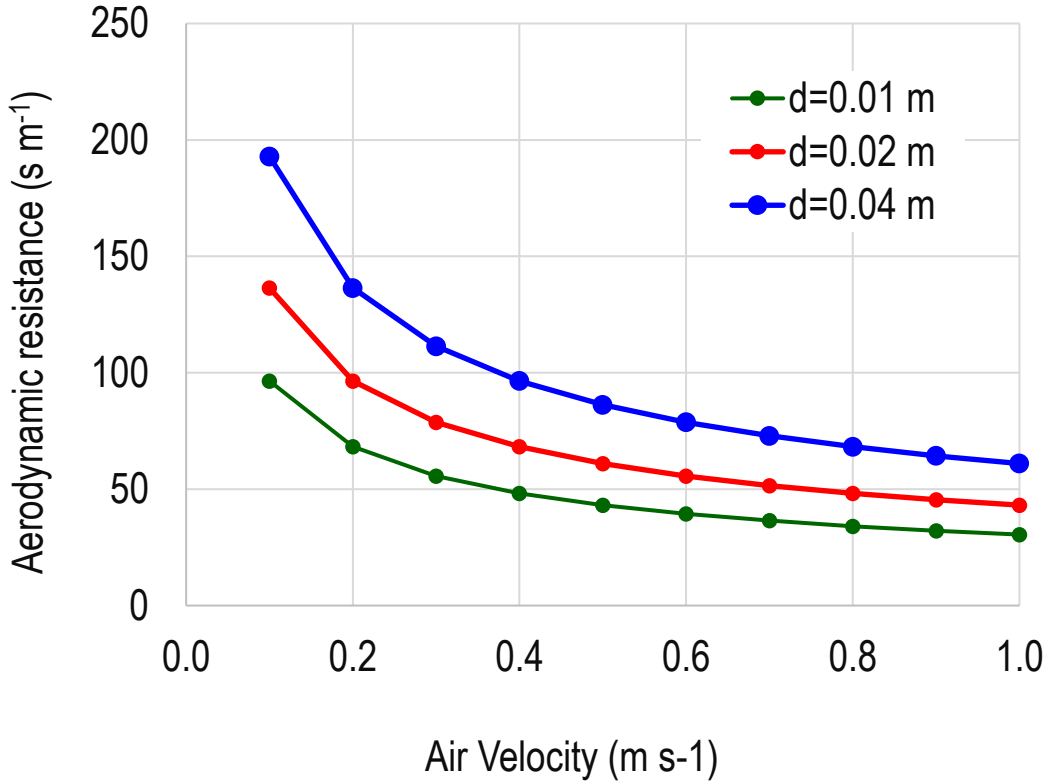
- **Tipburn of lettuces:**
    - A result of calcium deficiencies in growing tissue
    - Ca is taken up and transported by mass flow in xylem driven by transpiration
    - Leaf growing rate > Ca transportation rate



(Kitaya et al., 2000)

Boundary layer thickness and Aerodynamic resistance affected by leaf dimension and air velocity





[$Ra= 305\ (d/u_{\infty})^{1/2}$, Ra= aerodynamic resistance, d=characteristic leaf length, u_{∞}= non-disturbed air speed]

University of Arizona Urban Agriculture Vertical Farming Facility (UAg Farm)

1. Research, Teaching and Outreach Facility
2. Enhancing infrastructure, research, teaching and outreach capacity for urban agriculture, vertical farm, food/water/energy nexus.
3. University-Industry partnerships for research, technology developments and educational and internship programs.

USDA

Grodan

AEROFARMS

RIJK ZWAAN

RAYN GROWING SYSTEMS

heliospectra

RIDDER

ENZA ZADEN

PanAmerican Seed

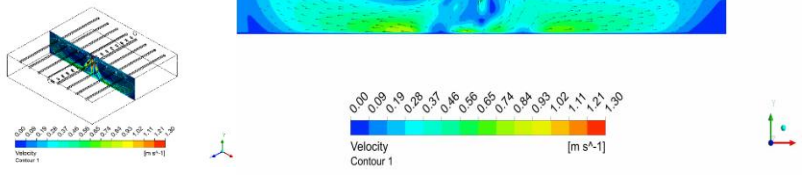
Computational Aerodynamics for Improved Air Conditioning & Distribution Systems

(Y. Zhang and Kacira, 2020)

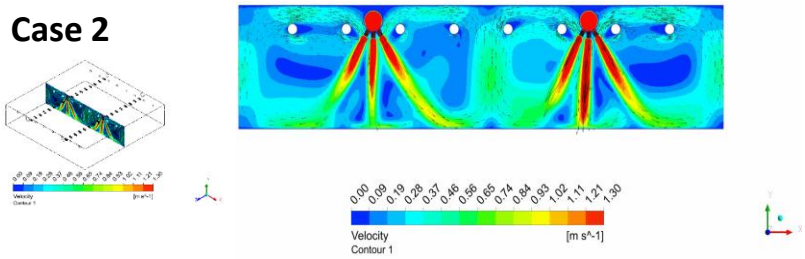
Controlled Environment Agriculture Center

Air Velocity

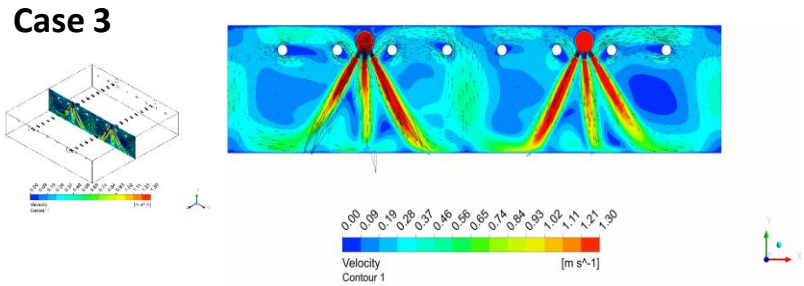
Case 1



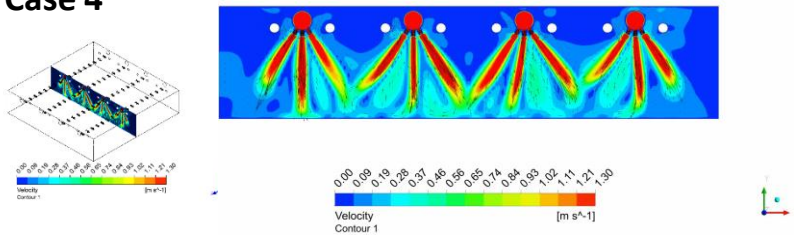
Case 2



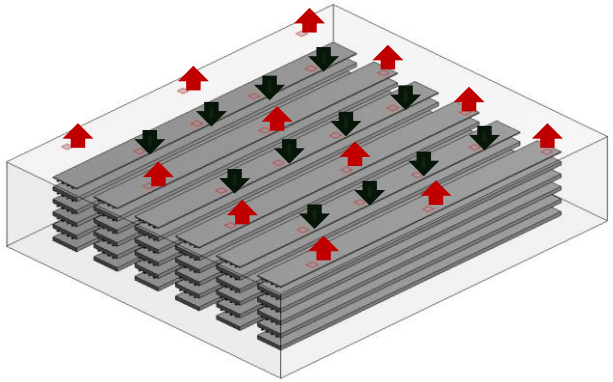
Case 3



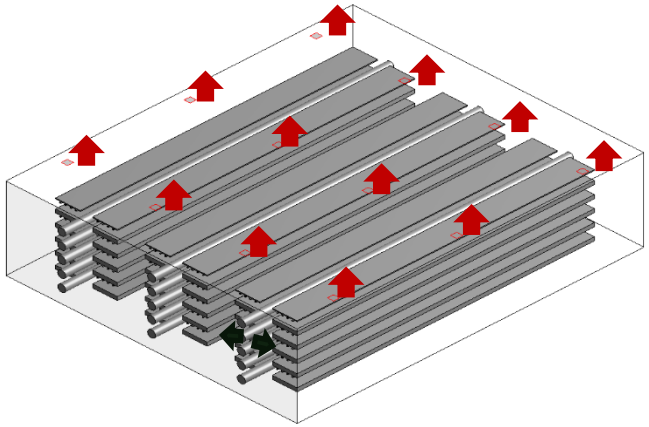
Case 4



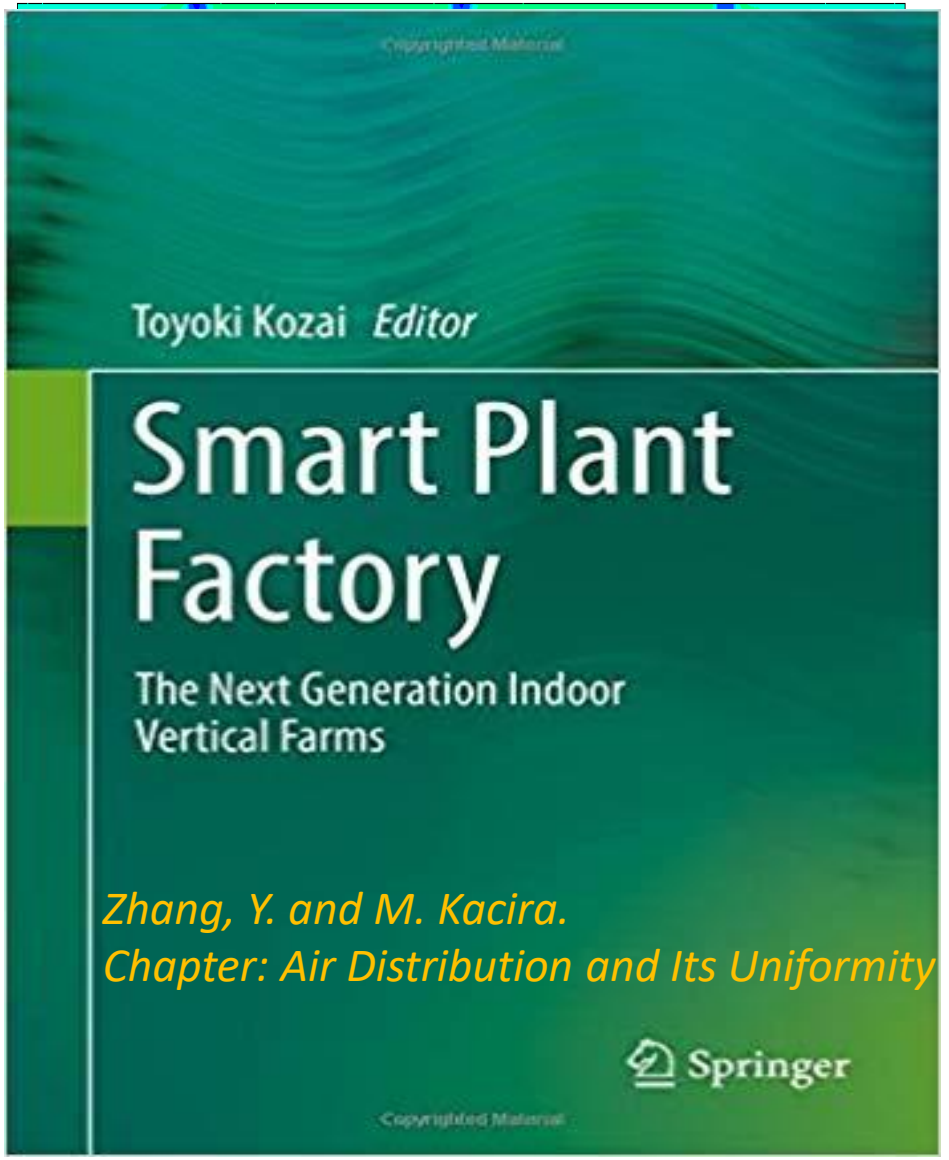
Design A



Design B

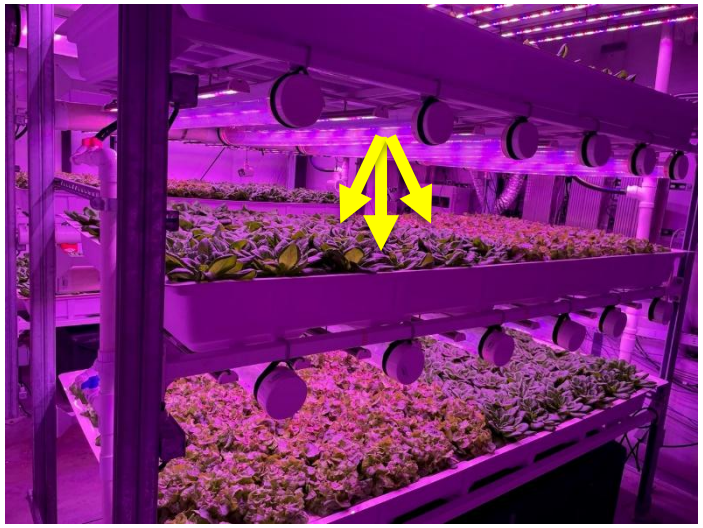


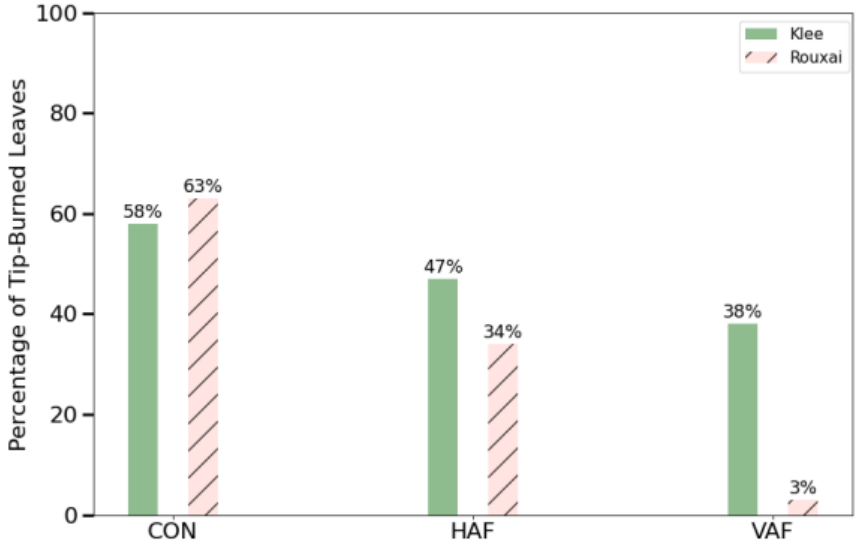
Air Temperature



Constant Vertical vs Horizontal Airflow to mitigate Tipburn

(C. Kaufmann, MS 2023)





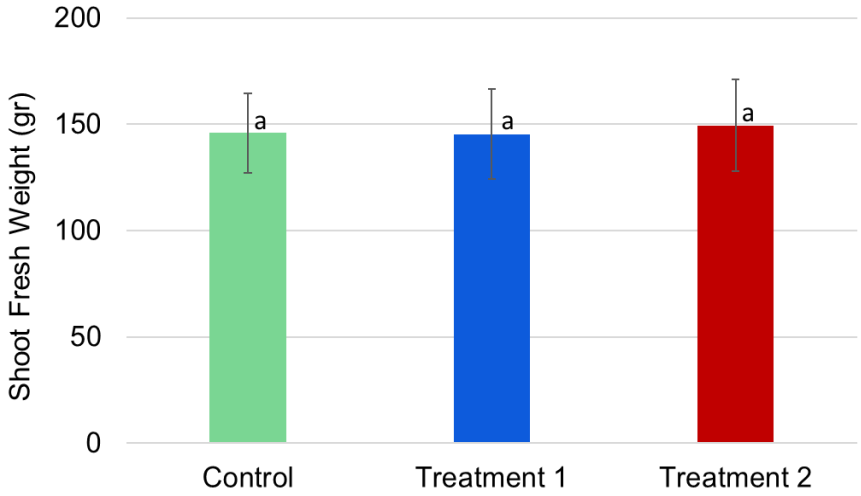
Intermittent Airflow to mitigate Tipburn and Energy Savings

(E. Dzeketey, MS 2024)

Control: Constant vertical airflow from transplanting to harvest

Treatment 1: Constant vertical airflow starting at the beginning of Week 3 of growth

Treatment 2: Intermittent vertical airflow during photoperiod starting at Week 3



Statistically insignificant (Tukey-Kramer HSD test, α = 0.05)

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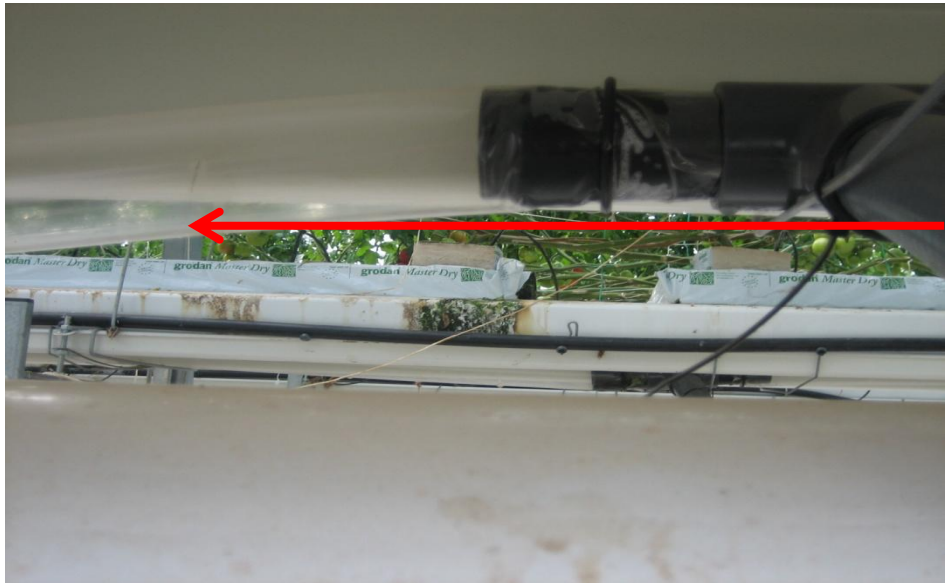
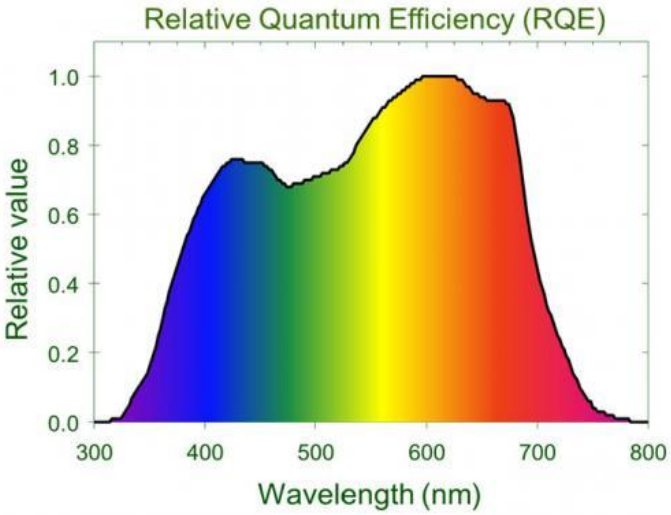
CO2 Enrichment

- Increase plant growth rate when high light levels
- Ventilation to replenish to ambient CO_2 levels
- Combustion byproducts
  - CO2, but also ethylene and CO
- Condensing Boilers
  - Capture waste heat and generate CO_2
- Manufactured: CO_2 cylinders and tanks



- Distribution pipes for CO_2 enrichment
- With morning light before ventilation
- Closed/semi-closed structures w/no ventilation
- 800-1200 ppm levels shown to be beneficial

Supplemental Lighting

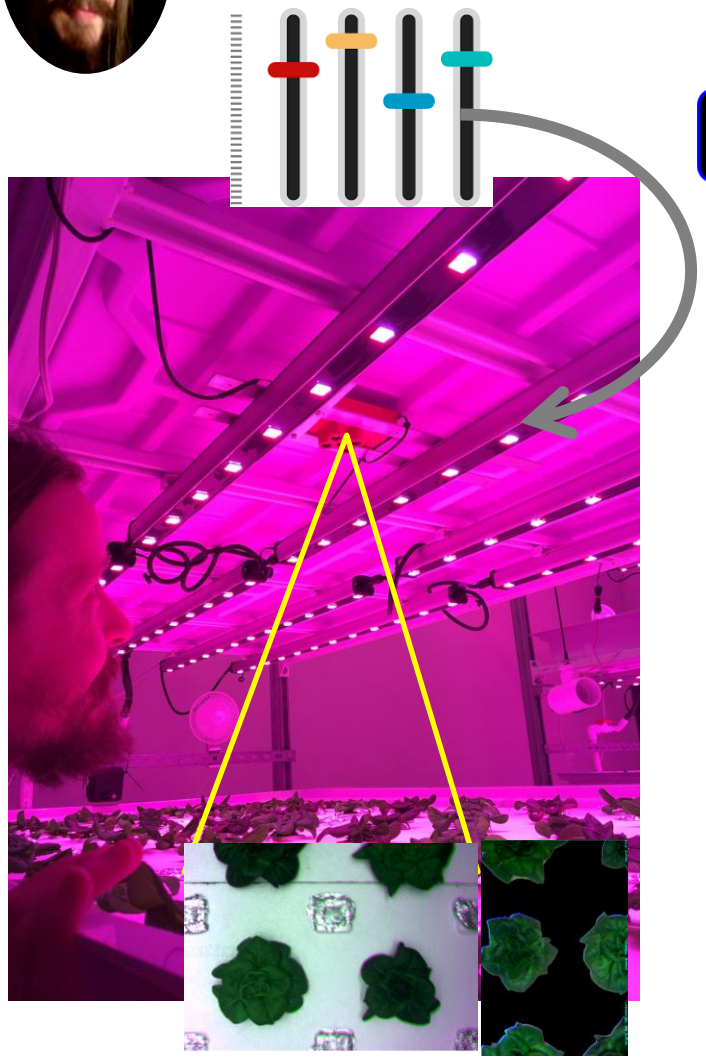


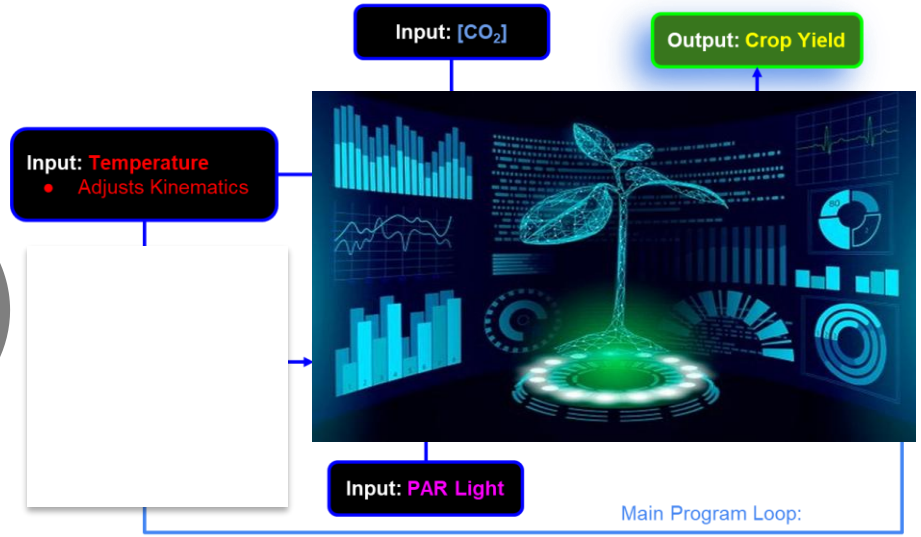
- Efficacy and controllability
- Research capabilities vs practical/commercial applications
- How to define wavelengths/need standardization
- What spectrums to design and manufacture for growers
  - General (easy/lower cost) vs boarder spectrum
  - Cap-Ex and Op-Ex
- ROI for LEDs for growers
- Fixture designs and deployments for improved Light Use Efficiency (LUE)
- Crop breeding to enhance LUE

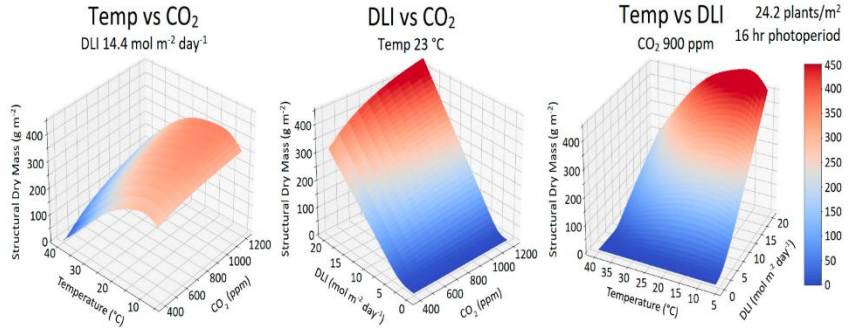
Phytometric Feedback Based Decision Support Tools for Optimizing Vertical Farm Resource Use Efficiency

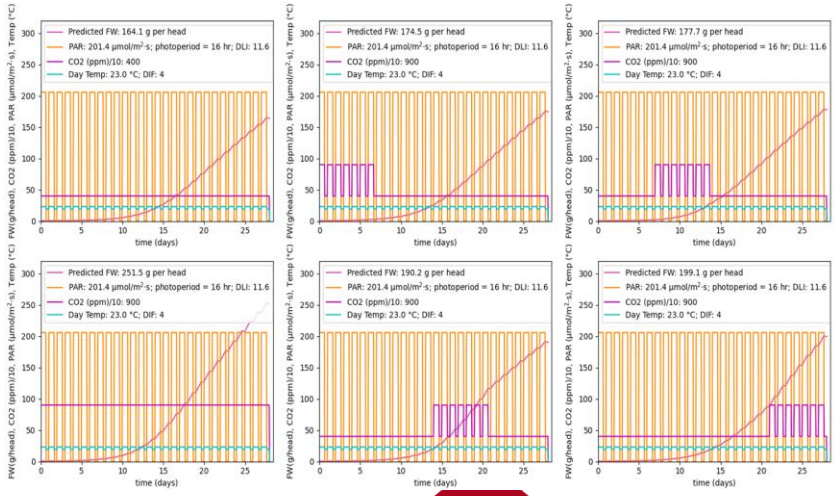
Controlled Environment Agriculture Center

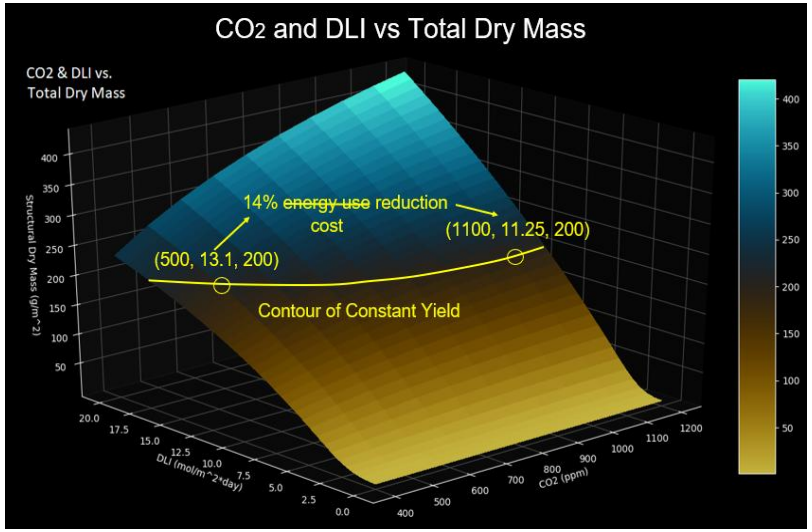
(KC Shasteen, MS 2023)



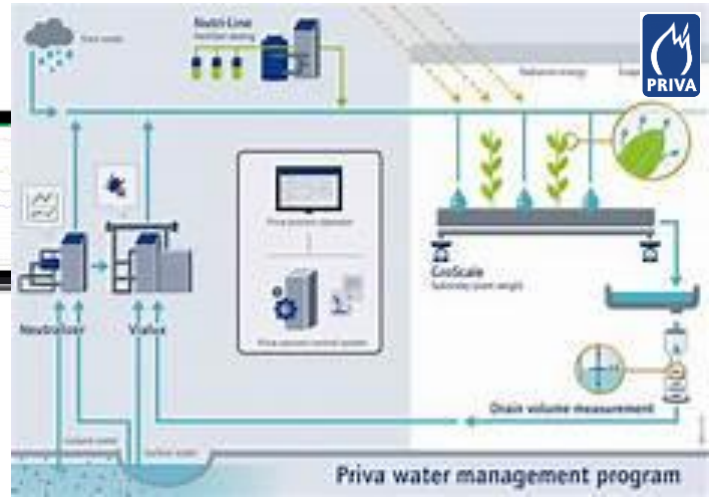




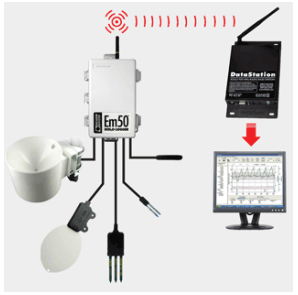




Climate Control



Sensors


Em50
DataStation


HOBO
Temp
onset


apogee
INSTRUMENTS
Made in USA

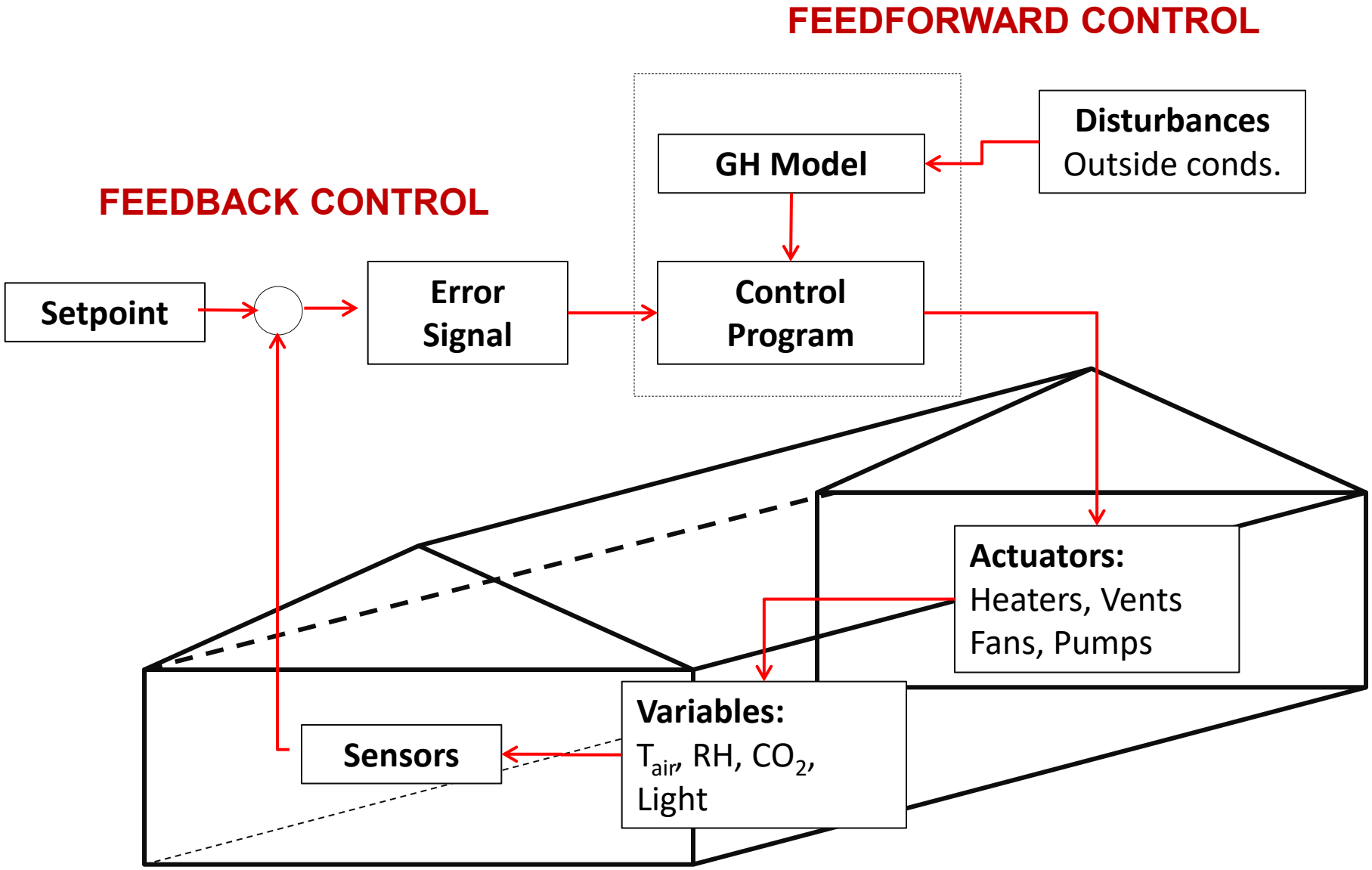

PLEASE DON'T TOUCH ME !
HOW CAN I MONITOR YOU ?
Plant Empowerment


STE


PH & Conductivity Monitor


PRIVA

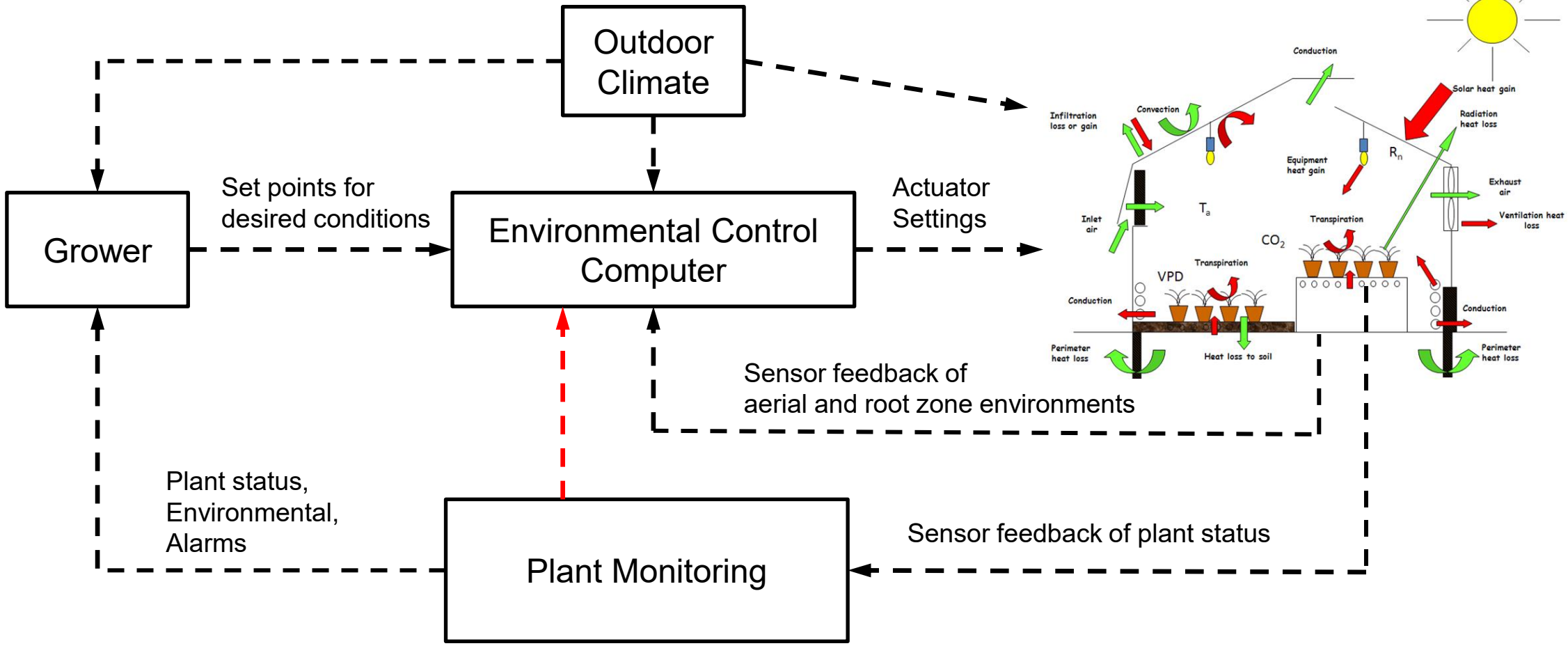
Environmental Control System



Environmental Controls:

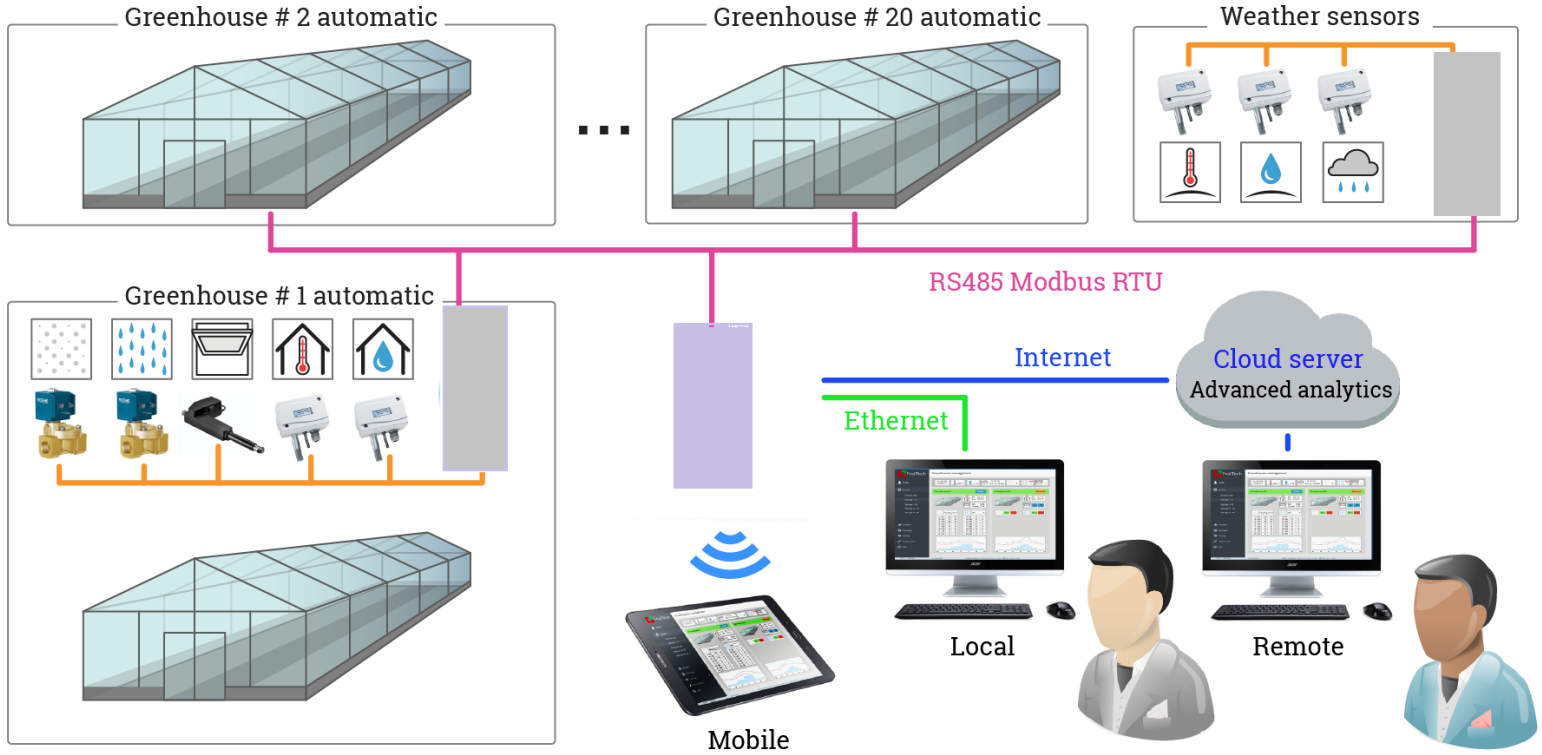
Measure plant's physiological responses using sensors and use that information for control. Such approach is called "Speaking Plant Approach"

- **Speaking Plant Approach**
  - Considering ***Plant Physiological*** aspects
  - Considering both ***the Physics of the Environment*** and ***Plant Physiological*** aspects

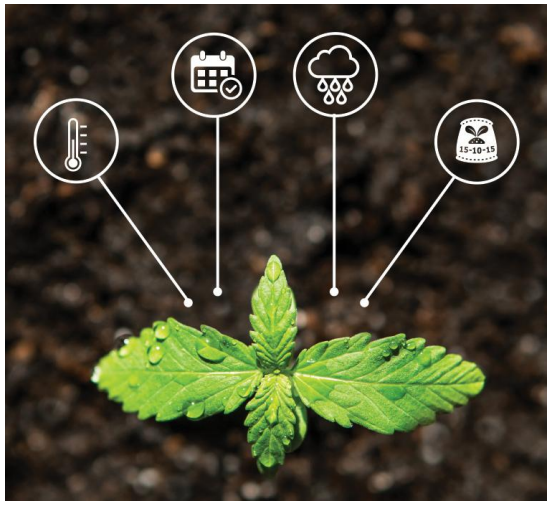


Trends and Opportunities

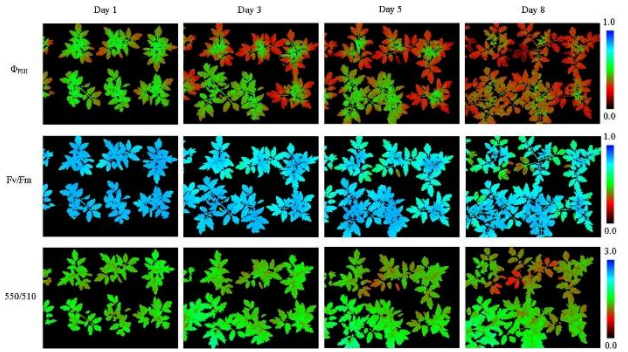
Internet of Things (IoT) and Cloud Based Service for Data Access/Management

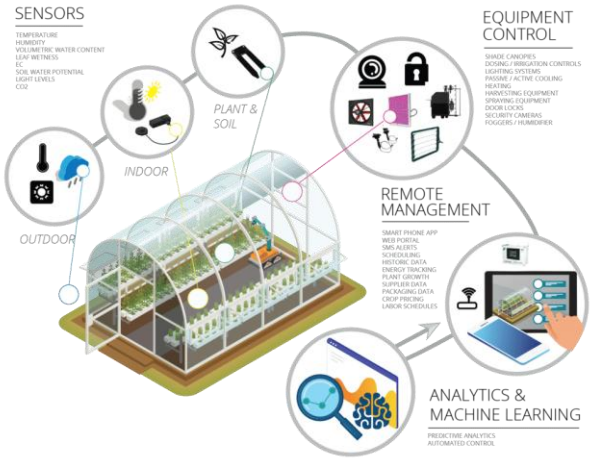


Trends in Greenhouse Environmental Controls

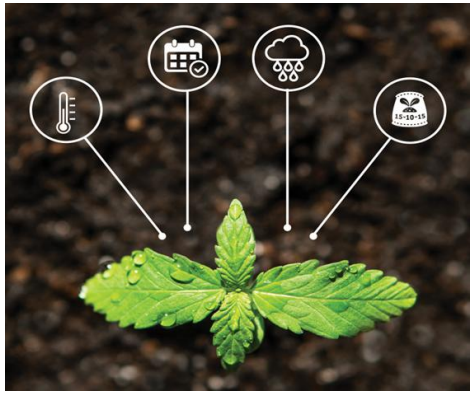


- plant centric environmental controls
- objective measurements vs. “green fingers”
- timely detection for plant health and growth : “seeing the invisible”
- remote access and control capabilities, IoT integration
- decision support systems
- autonomous control



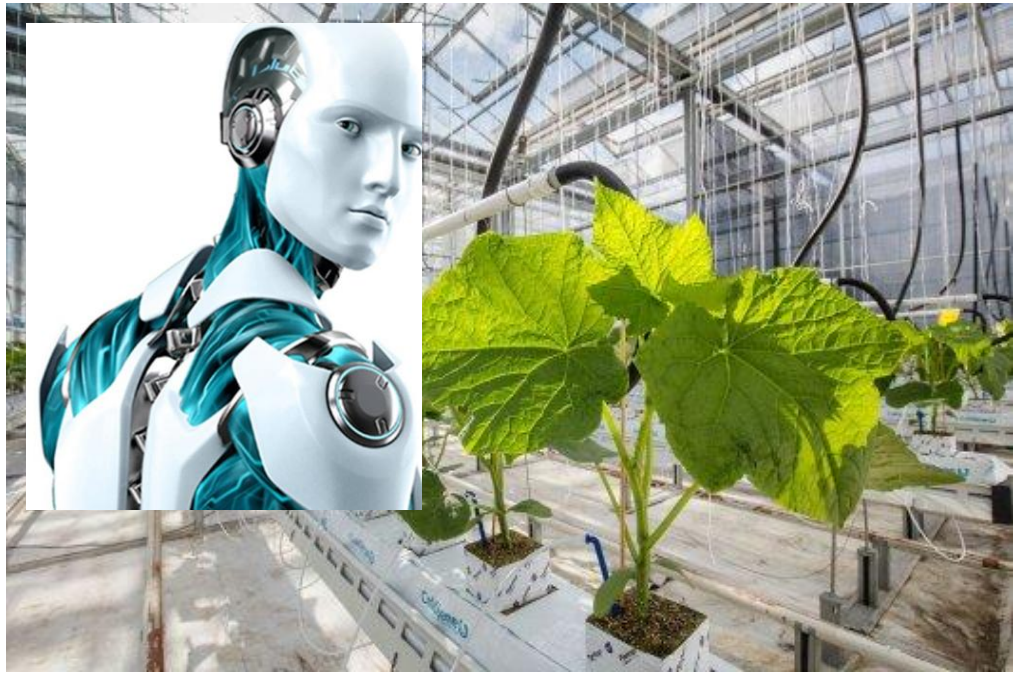


Artificial Intelligence is an empowering tool!



Digital Twins

VS

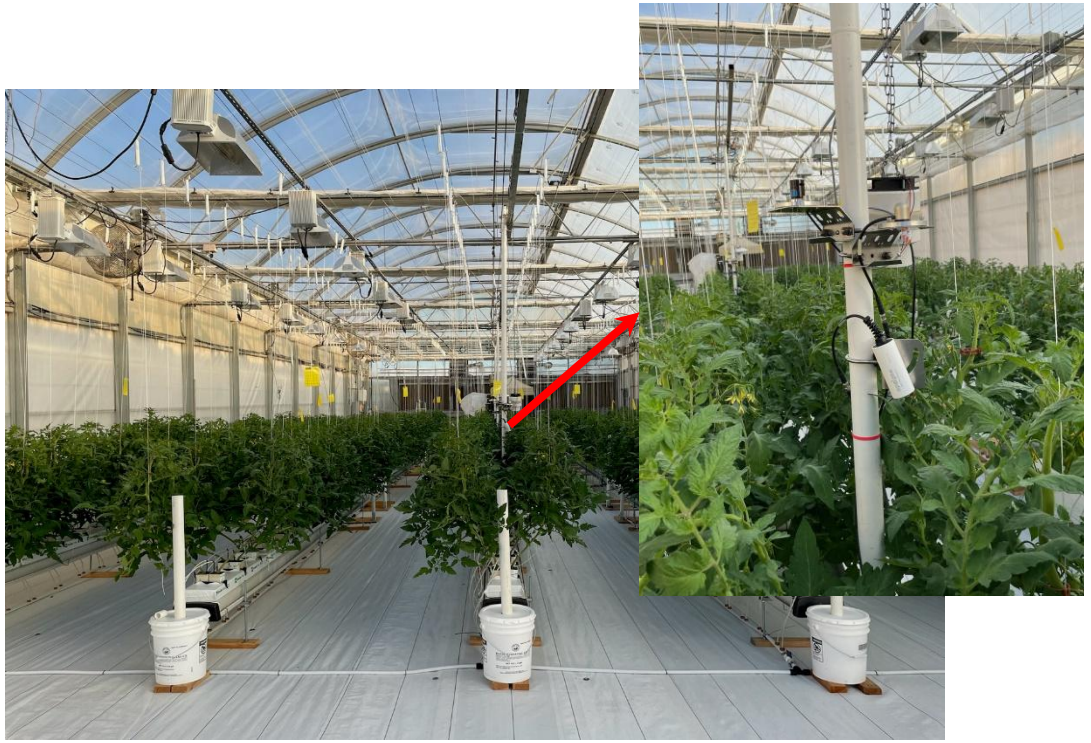


ADVANCEA: Advancing controlled environment agriculture through data-driven decision making and workforce development

AI Integrated Greenhouse Environmental Control

(Valencia Islas, Mahato, Conrad, Kacira, 2023-2027)

Objective 1: Development of a data- and model-driven decision-making platform
Objective 2: Validating the efficacy of new data- and model-driven decision making
Objective 3: Understanding the socioeconomic aspects of greenhouse technology adaptation
Objective 4: Engaging our stakeholders through professional learning opportunities that contribute to workforce development



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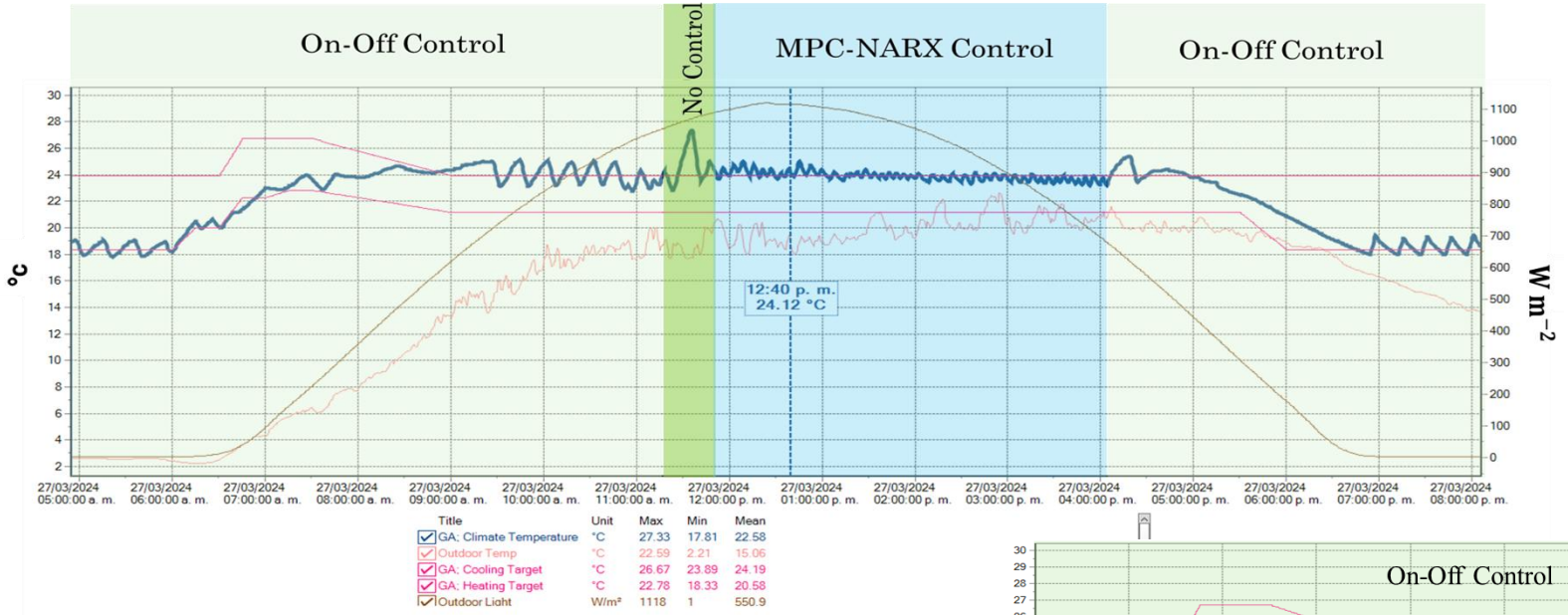
The Ohio State University | The University of Arizona | Cornell University | Rutgers The State University of New Jersey | koidra | HORT AMERICAS

Model Predictive Control Strategy

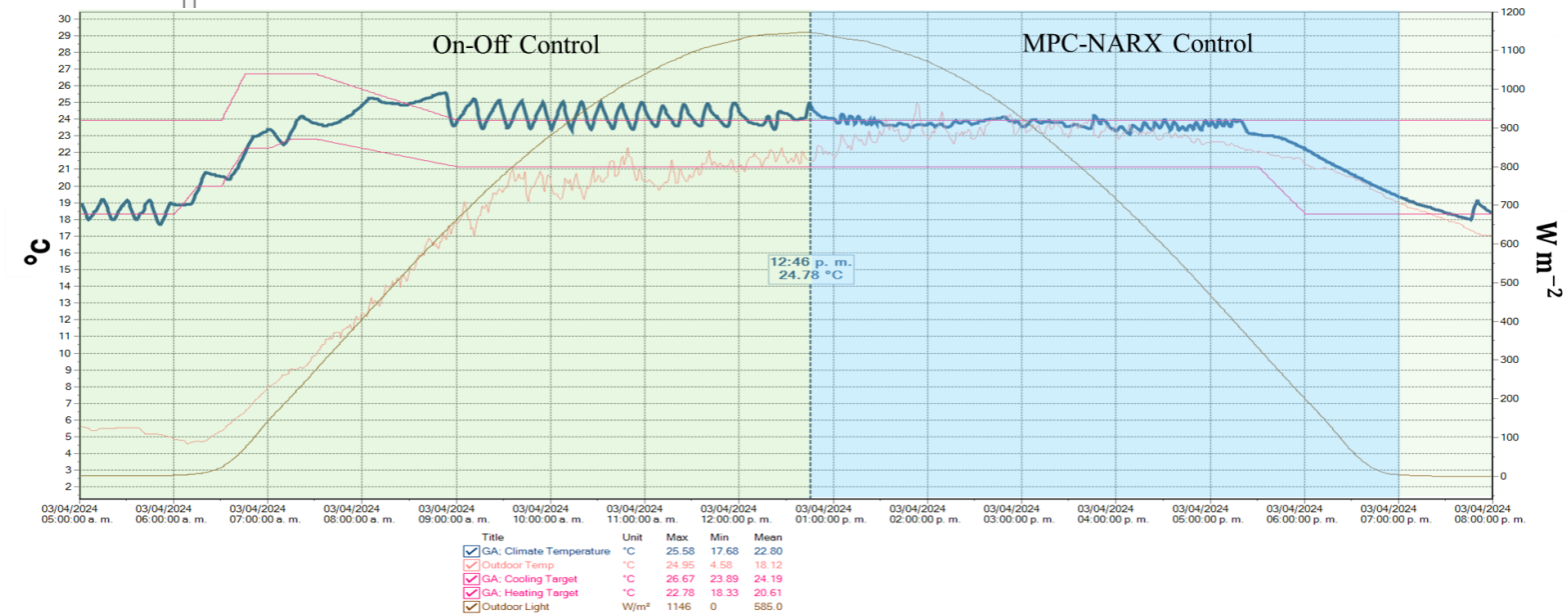
THE UNIVERSITY OF ARIZONA
BIOSYSTEMS ENGINEERING
Controlled Environment Agriculture Center

March-27th



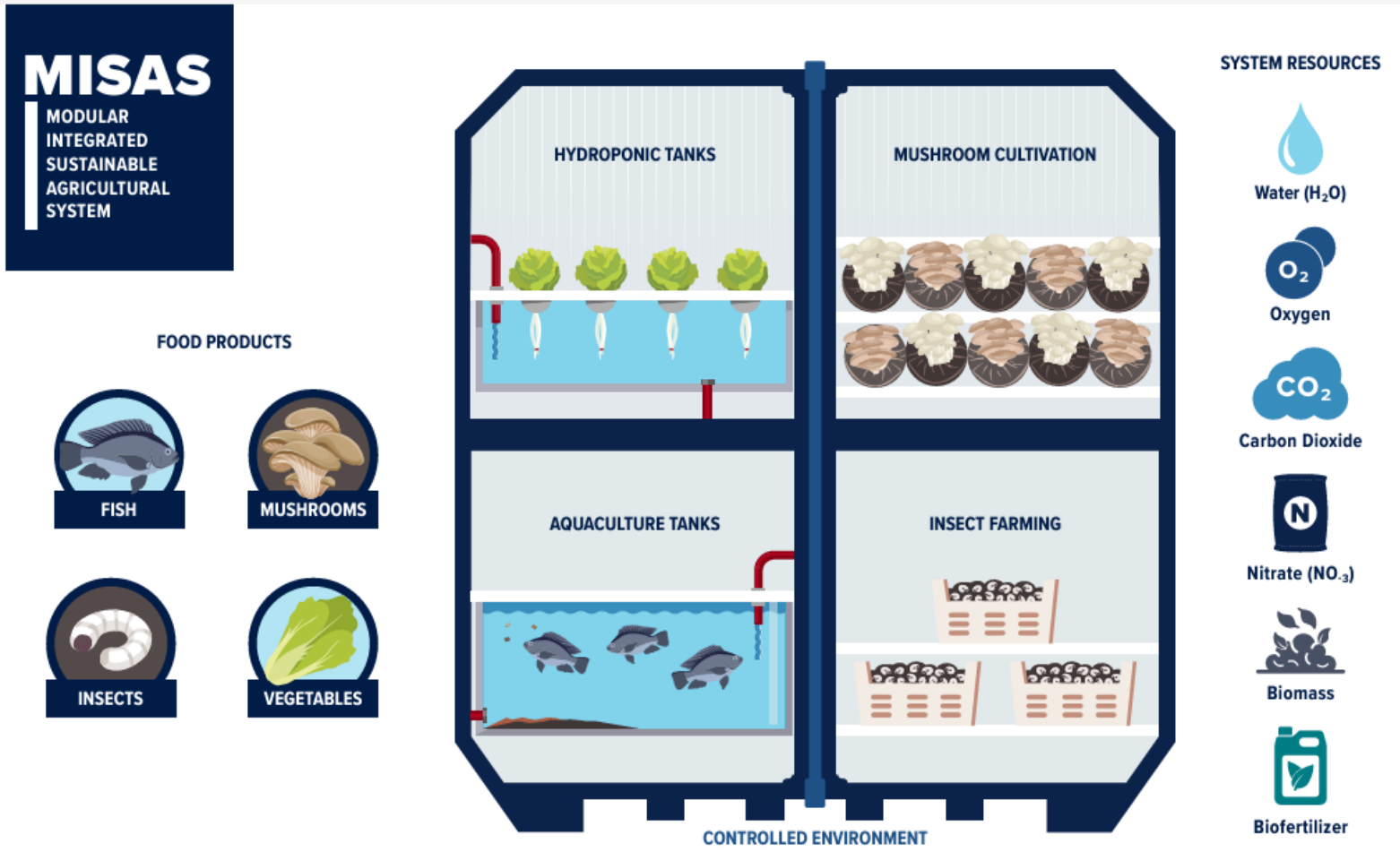
Half On-Off
Half MPC-NARX

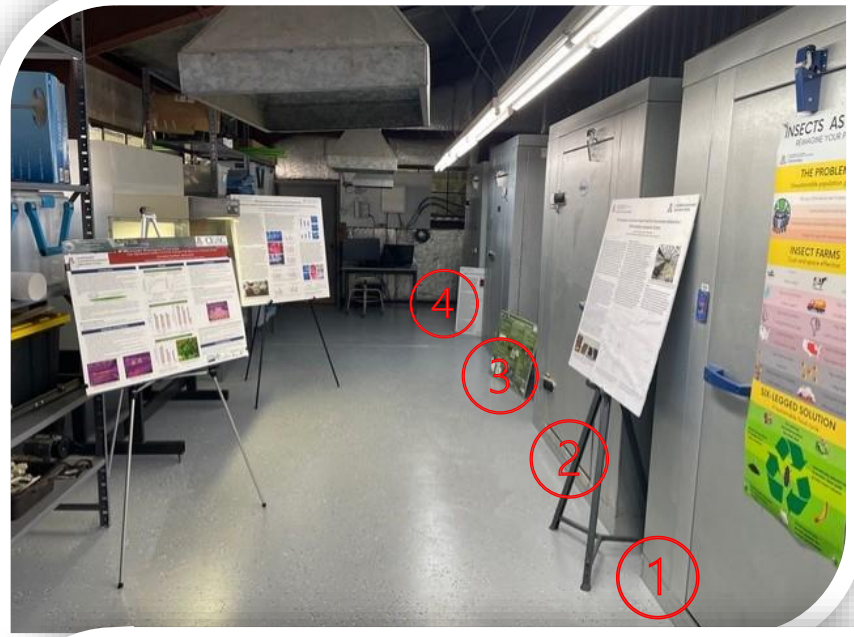
April-3rd

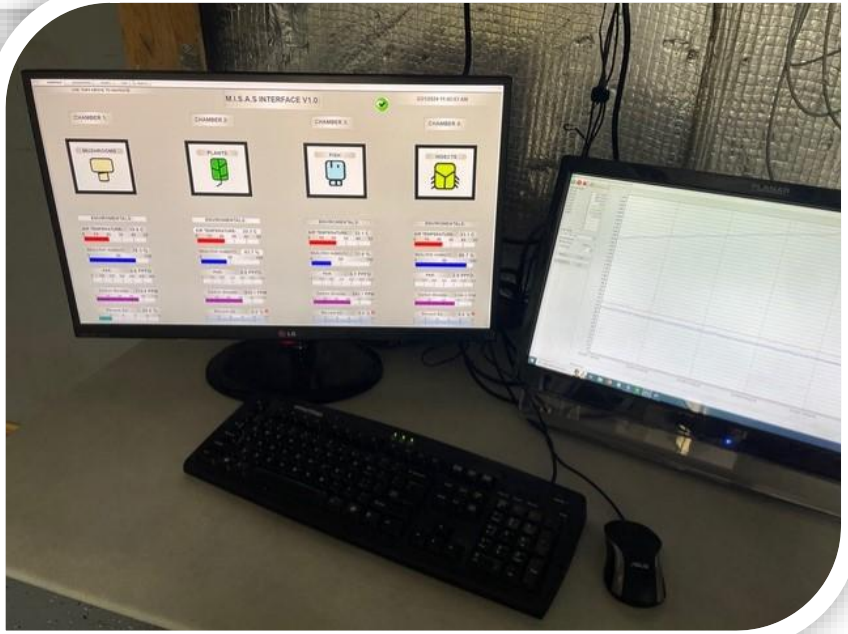


Modular Integrated Sustainable Agriculture System (MISAS)

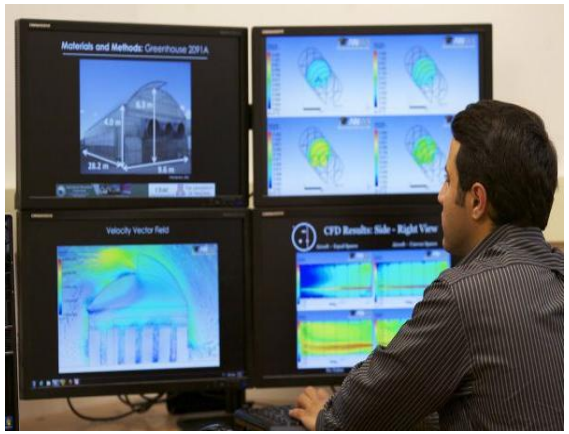
(G. Davidowitz, K. Fitzsimmons, B. Pryor, M. Kacira)







Thank you!



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