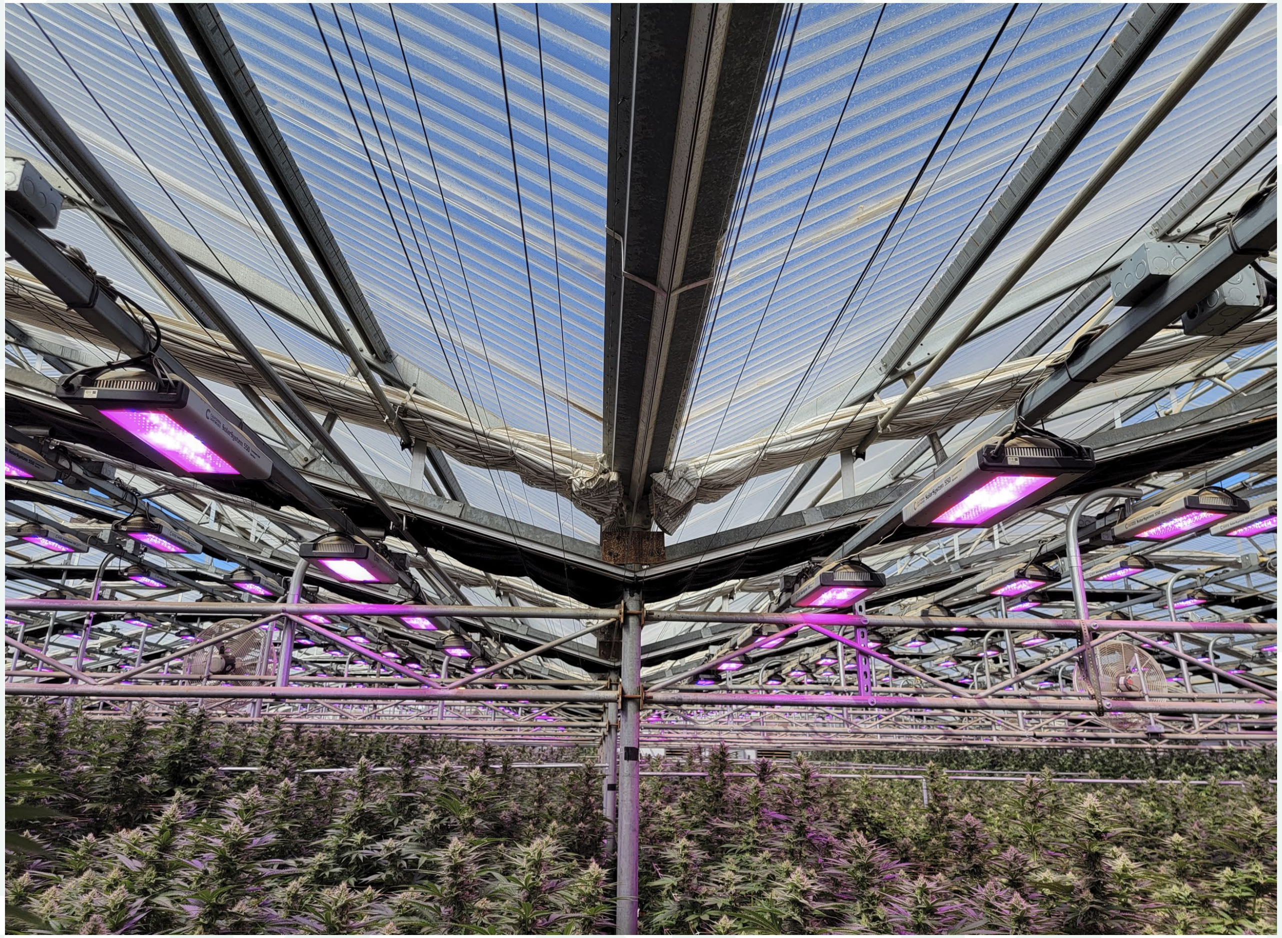
Greenhouse Design

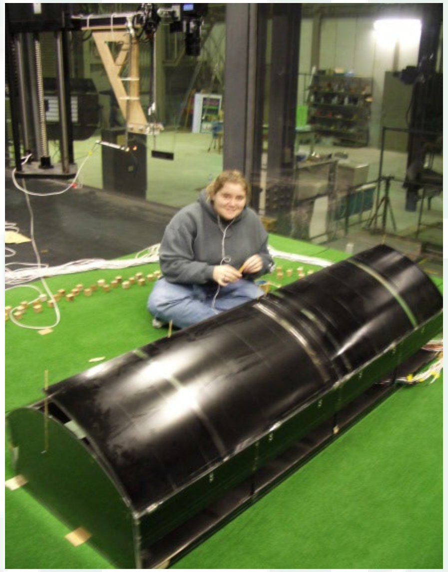


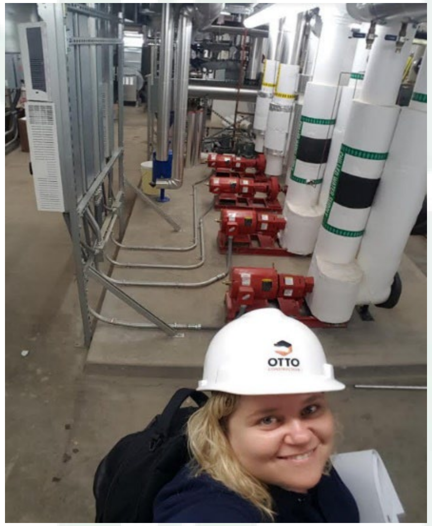
Presented by:
Dr. Nadia Sabeh, PE
President, Dr. Greenhouse, Inc.

Dr. Greenhouse

Introduction

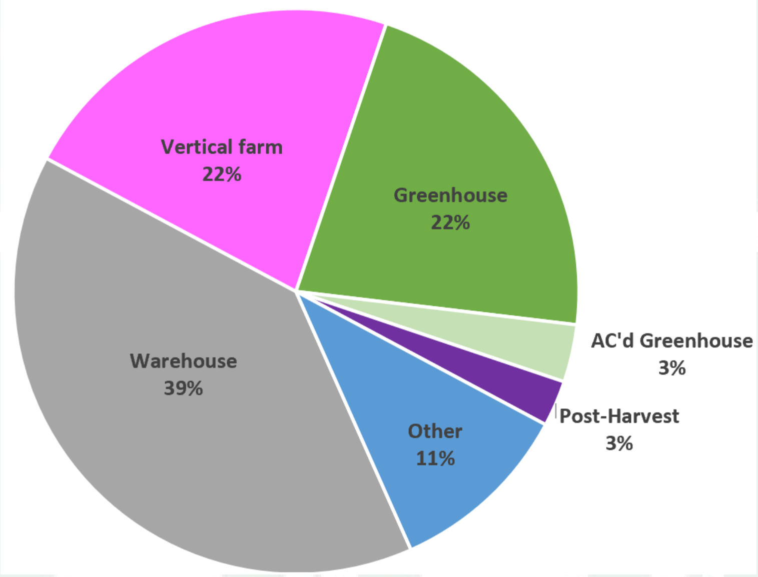
- 25 years ago...Mushroom Farm Internship
- PhD in Agricultural Engineering
  - University of Arizona (CEAC)
  - GH Evaporative Cooling
    - WUE and HPF strategies
  - Natural Ventilation
    - Wind tunnel studies in Japan
- PE in Mechanical Engineering
  - HVAC Design and LEED
- Dr. Greenhouse, Inc.

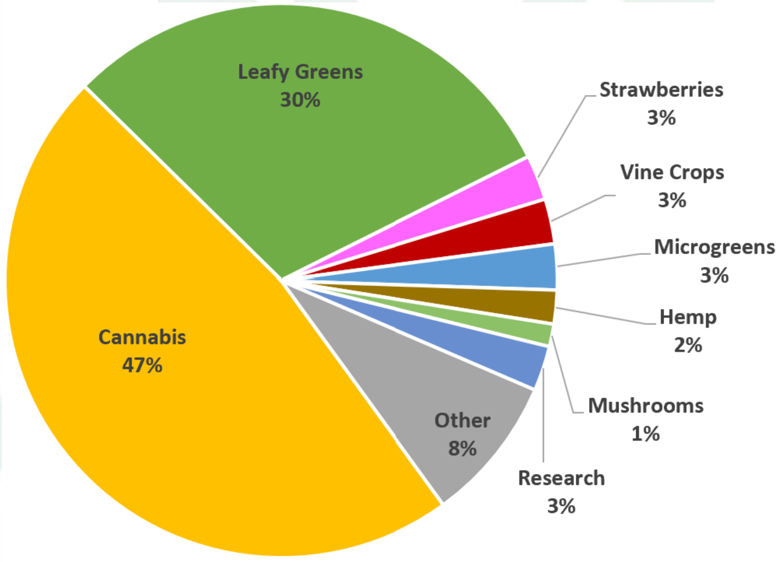


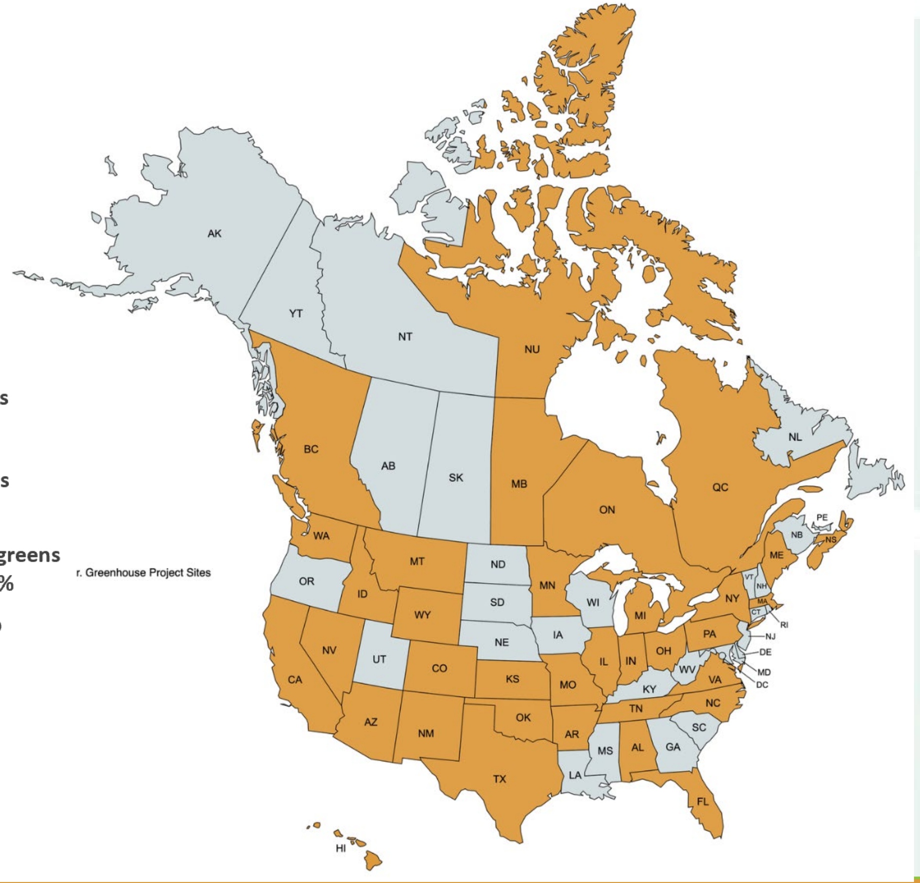


Dr. Greenhouse, Inc.
(Est. 2017, Sacramento, CA)

- Mechanical & Agricultural Engineering Firm
- Design and Optimization of HVAC and Environmental Control
- Greenhouses and Indoor Grows
- Mix of Projects
- Mix of Clients







Dr. Greenhouse, Inc. (Est. 2017)

- Greenhouse Services we Provide
  - Cooling, Heating, Humidity Calculations
  - Weather Analysis
    - Site selection
    - HVAC equipment selection
    - HVAC/Lighting optimization
    - Supp. Lighting needs
  - GH Quote 3rd Party Review
  - Controls sequencing
  - Custom HVAC design
  - Code Analysis
  - Education and Training

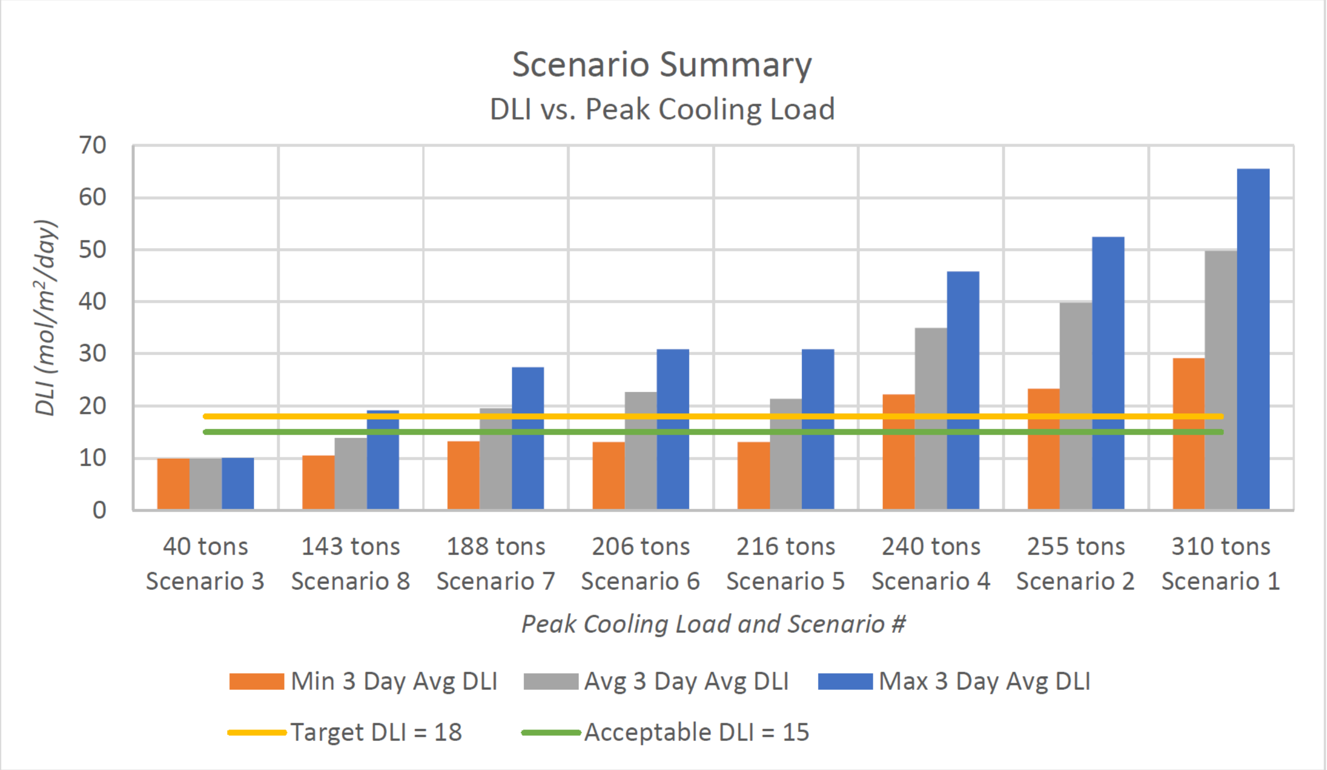


Figure 6. Summary of DLI vs. peak cooling load for the scenarios considered (Scenarios 1-8)

Questions I get asked frequently

1. What is a greenhouse?

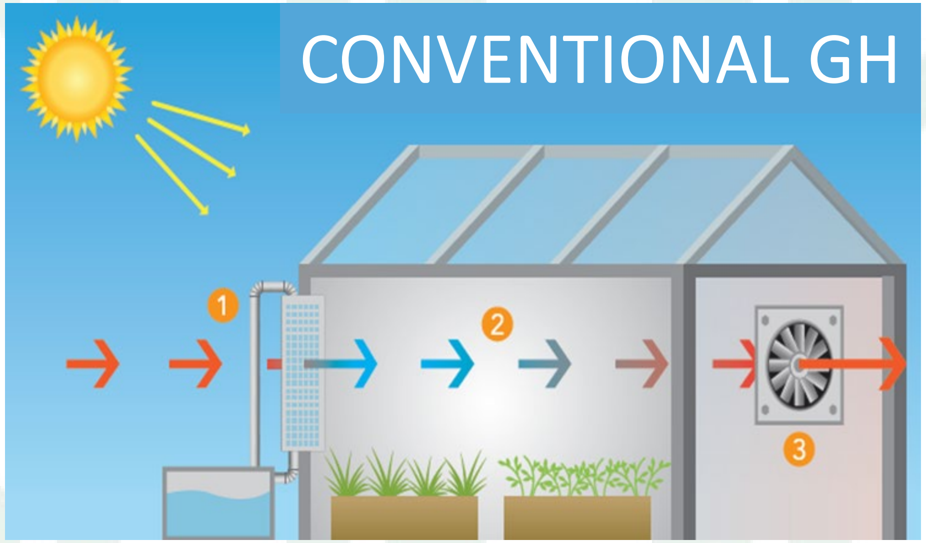
2. Can you grow consistently year-round in a GH?

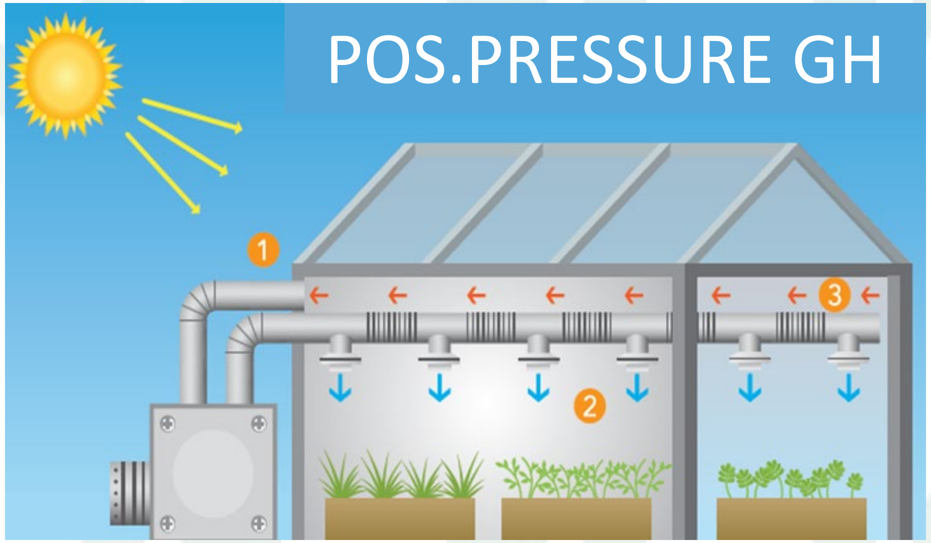
3. Are GHs more sustainable than indoor grows?

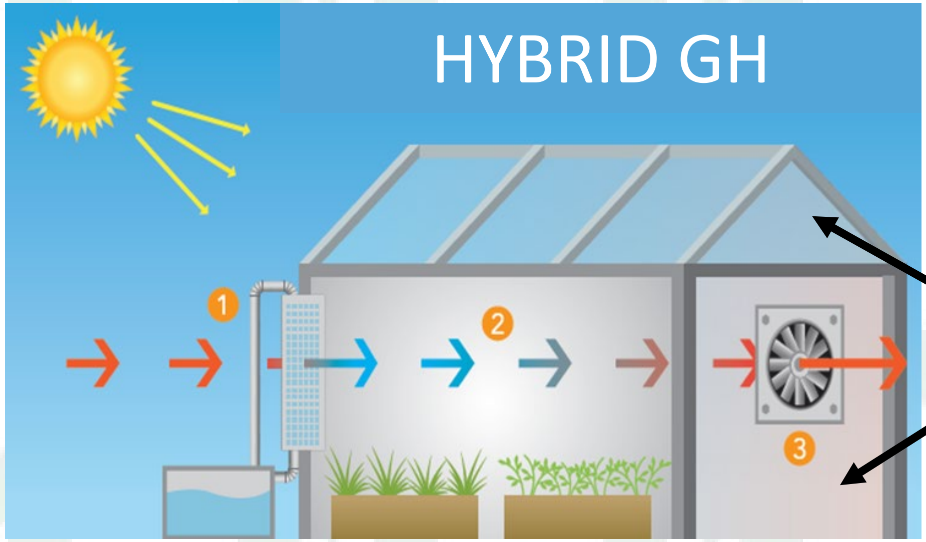
4. Are GHs cheaper than indoor grows?

5. Can you grow the same quality crop as indoor?

What is a Greenhouse?







- Clear Roof
- Metal Walls
- Conventional
- Pos. Pressure

Greenhouse Structures/Styles

Why a Greenhouse?

Why a Greenhouse?

SUNLIGHT!!

"Free" Light Energy

Courtesy Marijuana Venture

Why a Greenhouse?

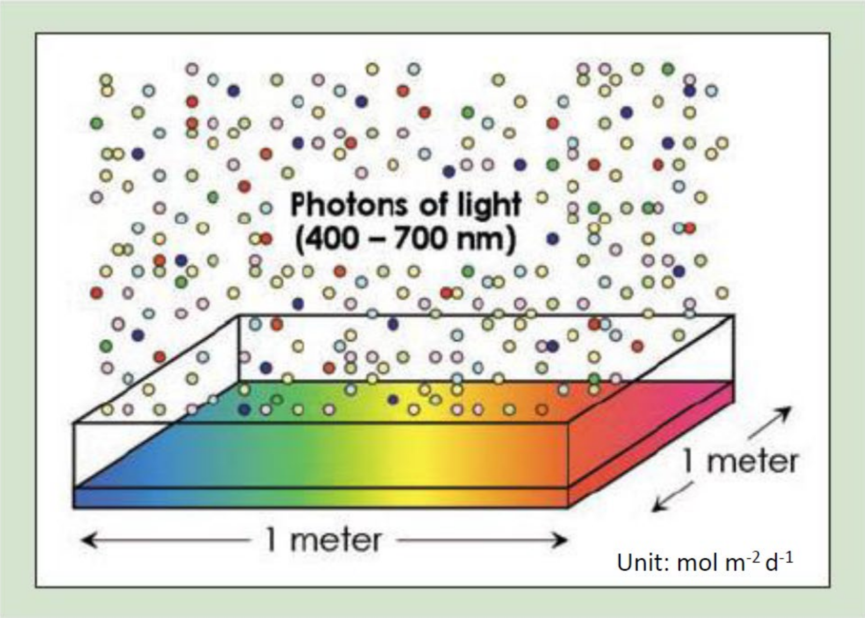
SUNLIGHT!!

"Free" Light Energy, but…

Sunlight not equal everywhere or year-round or under every cover.


Courtesy Marijuana Venture

Daily Light Integral (DLI)



(Runkle, 2006)

Leafy Greens = 12-18 mol/m^2/day

Strawberries = 20-25 mol/m^2/day

Tomatoes = 30-35 mol/m^2/day

Cannabis Veg = 30-40 mol/m^2/day

Cannabis Flower > 40 mol/m^2/day

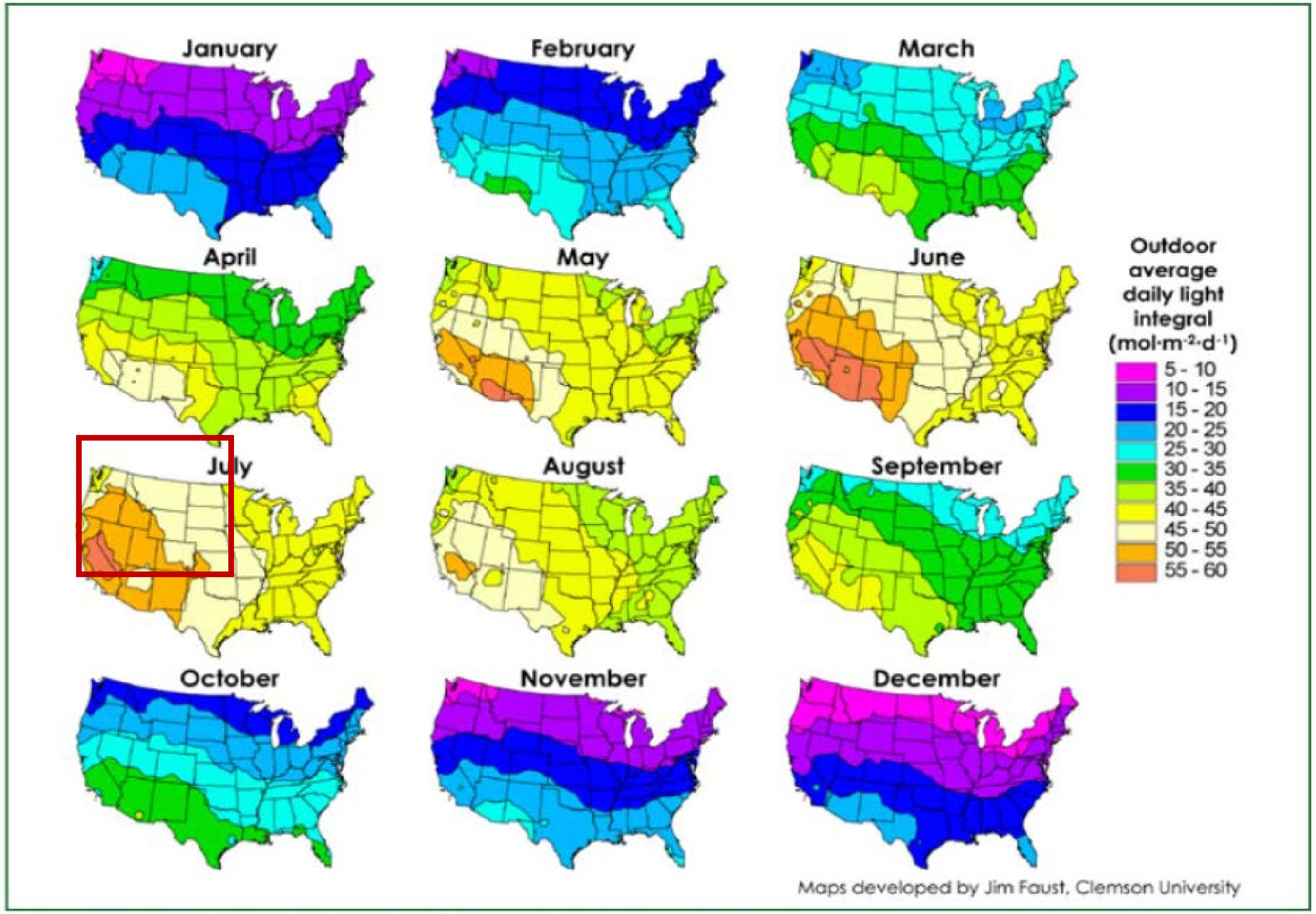
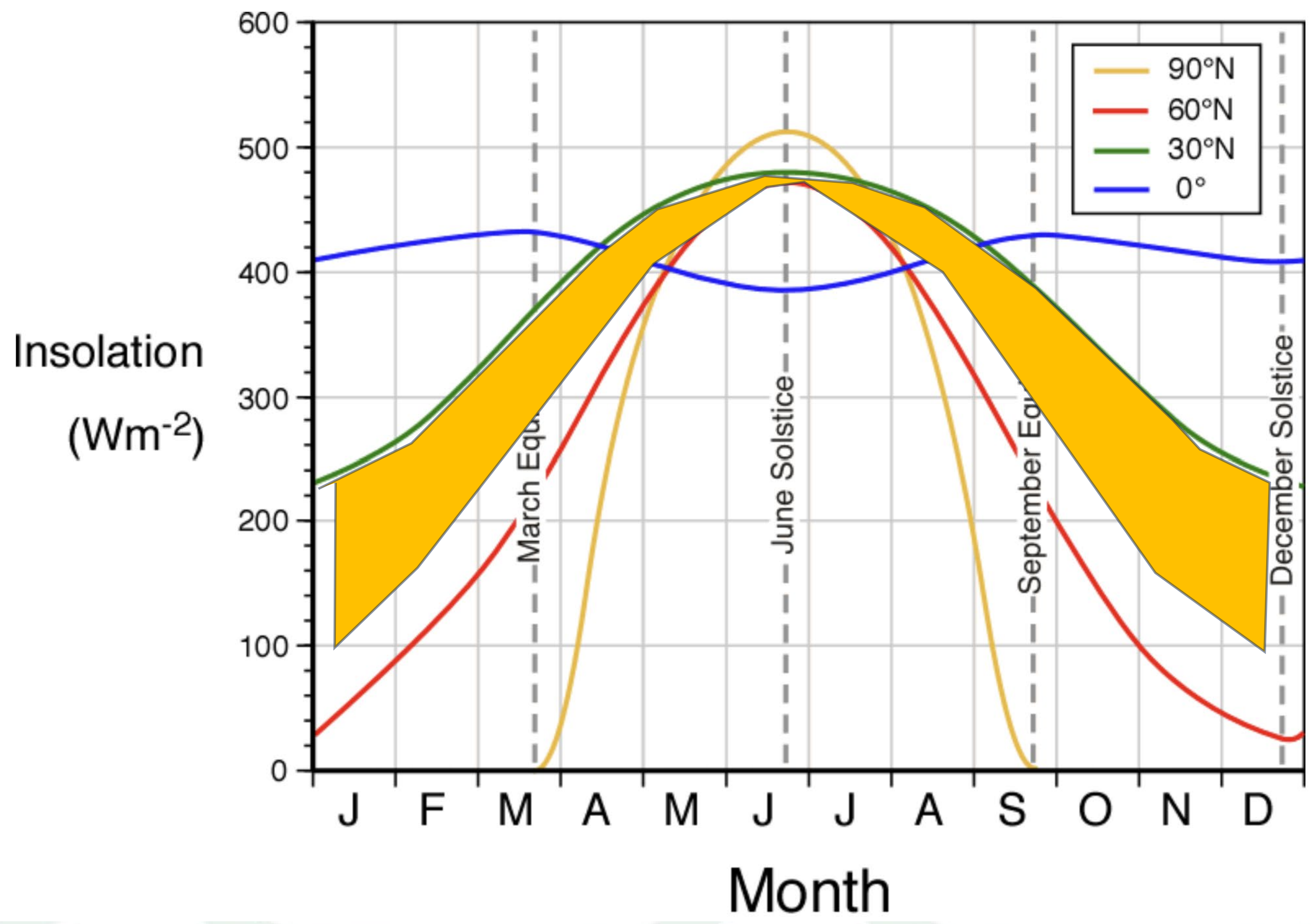


Figure 1. Maps of monthly outdoor DLI throughout the United States.

Source: Mapping monthly distribution of daily light integrals across the contiguous United States (Pamela C. Korczynski, Joanne Logan, and James E. Faust; Clemson University, 2002)

Sunlight Availability: Location and Seasonal Differences

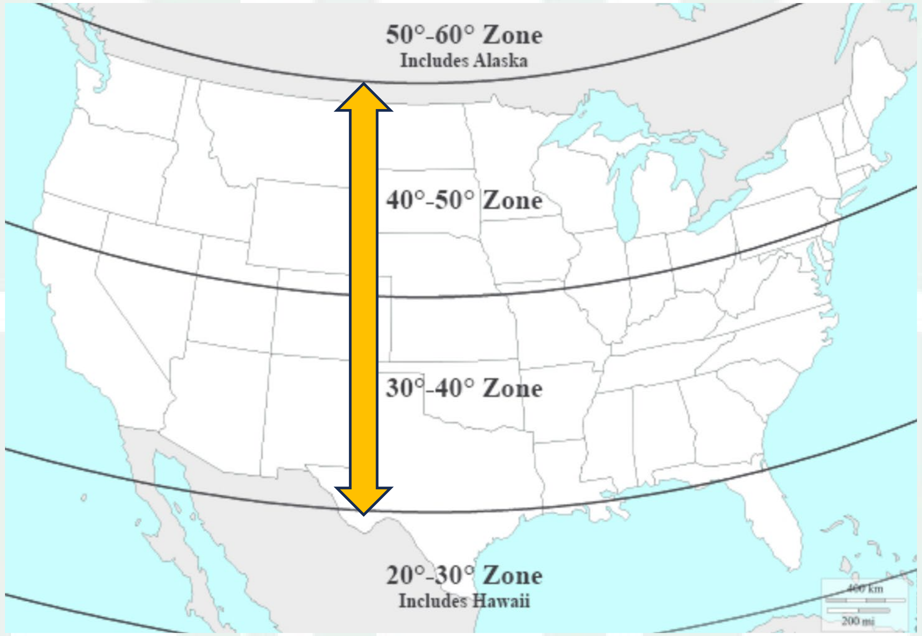


90° North Pole

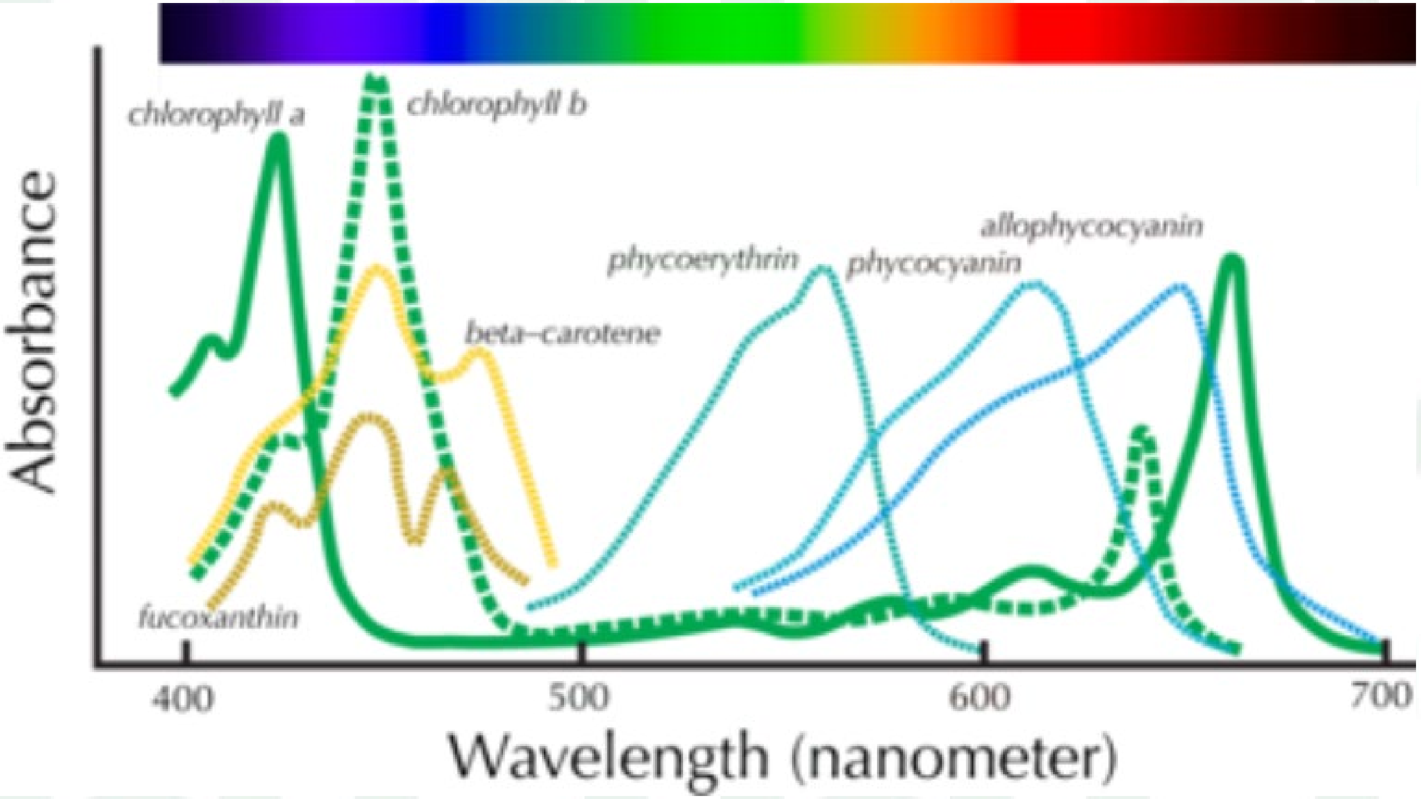
60° Alaska, Canada Northern Territories

30° Houston

0° Equator



Light: More than just PAR and DLI



Plant Physiology, 6th Edition, 2015

Several pigments absorb nearly all radiation between 400 to 700 nm!

↓↓

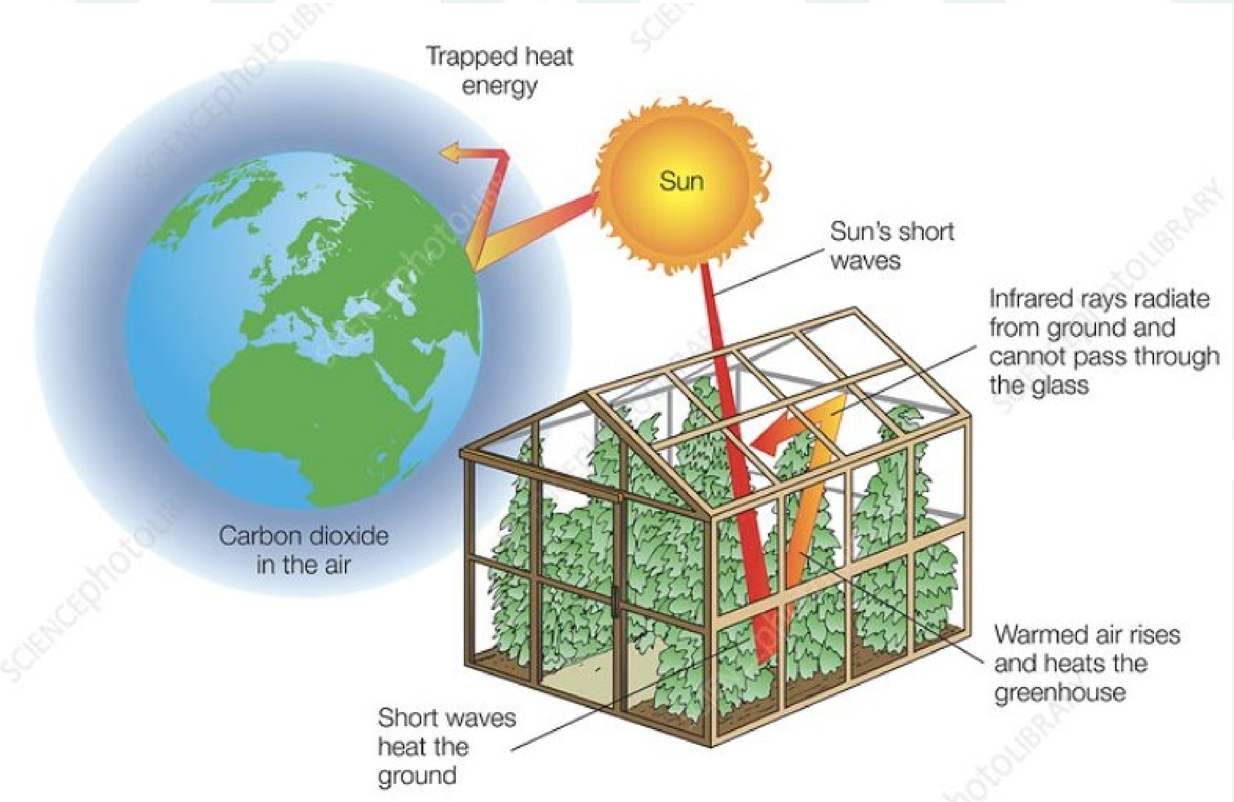
Secondary Metabolite Production:

→ terpenes, colors, nutrients

With light comes heat

The Greenhouse Effect!

Great in the Winter, Horrible in the Summer.



Light and Heat: Greenhouse Covers

Greenhouse Covers Comparison

COVER	LIGHT TRANSMISSIVITY	HEAT TRAPPING	COMMENTS
Glass	High (> 93%)	High	Great for northern, cold climates
Plastic (polyethylene, polycarbonate)	High (88-93%)	Low	Good for sunbelt, but breaks down in sun
Acrylic	High (88-93%)	Low	Good for sunbelt, but collects dust and gets brittle in sun
New: spectrum selective, UV inhibiting, IR inhibiting, solar electric	Medium (< 90%)	Low	Focus on selecting wavelengths for plants

Greenhouse Cover: California's New Energy Code

California Energy Code, Controlled Environment Horticulture Mandatory Measures (Title 24, Part 6, Section 120.6(h), Effective Jan 1, 2023)	
Indoor Growing	**Greenhouses**
Horticultural Lighting - PPE ≥ 1.9 µmol/Joule	**Horticultural Lighting** - PPE ≥ 1.7 µmol/Joule
Electrical Power Distribution - Design electrical panels such that electrical energy use of horticultural lighting systems can be monitored and measured	**Building Envelope (Air-Conditioned Greenhouses)** - Opaque walls and roof: comply w/Section 120.7 - Transparent covers: glazings must have two or more layers separated by air, argon, or other gas
Dehumidification - Standalone dehumidifiers: comply with federal appliance standards - Integrated HVAC system: meet 75% of dehumidification reheat needs w/heat recovery - Chilled water system: meet 75% of dehumidification reheat needs w/heat recovery - Desiccant system: Only allowed when target dewpoint < 50F	**Space-Conditioning Systems** - Air conditioners, chillers, heaters, fans: comply with all applicable requirements (eg. mechanical, plumbing, and electrical codes associated with HVAC systems)
All New CEH Operations	
Time-switch lighting controls: - Install automatic or astronomical time-switch controls that can be programmed to operate lights at a minimum of two levels (Section 110.9(b)1) - Install controls that can automatically shut off lights (Section 130.4(a)4) - Inspect and test the functionality of time-switch controls (applicable sections of NA7.6.2)	
Multilevel lighting controls: Horticultural lighting levels must be adjustable up and down (Section 130.1(b).	

CEH Mandatory Measures: Greenhouses: Building Envelope

4. **Conditioned Greenhouses**, **Building Envelope**. Conditioned greenhouses shall meet the following requirements:

   A. Opaque wall and opaque roof assembly shall meet the requirements of Section 120.7; and

   B. Nonopaque envelopes shall have two or more glazings separated by either air or gas fill.

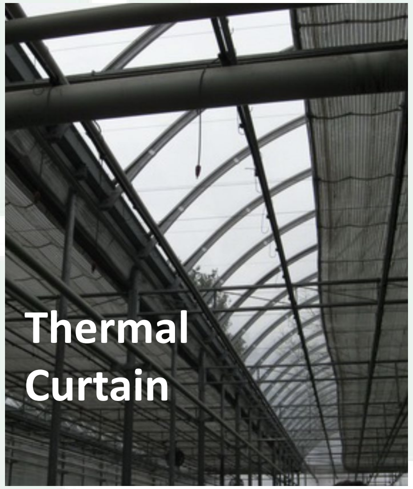
Interpretation:

- **No single-film glazing, corrugated polycarbonate, or glass**
- Options:
  - Double-inflated polyethylene
  - Twin-wall polycarbonate and acrylic
  - Double or triple-pane glass

Heat Management: Screens and Curtains

- Summer: Shade screens and coatings
  - Blocks heat from entering greenhouse
  - Reduces GH temp by 2-6°F (1-3°C)
  - Reduces cooling by 20-40%
  - Limit plant respiration and heat stress

- Winter: Thermal curtains
  - Traps heat inside greenhouse
  - Reduces heating by 20-30%



- Blackout Screens

Heat Management: Winter Heating

HEATING METHOD	EQUIPMENT TYPE	ENERGY SOURCE
Overhead	Unit heaters Hot water fan coils Radiant heaters	Fossil fuels
Perimeter **Snow melt**	Water/Steam Pipes Radiant	Fossil fuels
In-Aisle	Hot water pipes	Fossil fuels
Underbench/Root Zone	Heat mats Hot water pipes	Fossil fuels Electricity
Other	Lights Heat pumps	Electricity

Heat Management: Winter Heating

Heat Management: Summer Cooling

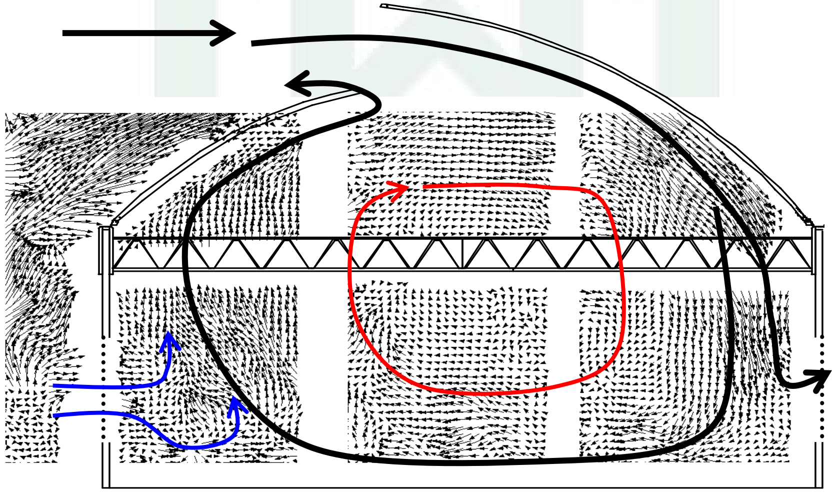
COOLING METHOD	EQUIPMENT TYPE
Ventilation	Passive (wind and buoyancy) Mechanical (fans)
Evaporative Cooling	Pad-and-fan (P&F) High-pressure fog (HPF)
Air Conditioning	Split DX Packaged DX Chillers
Root Zone Cooling	Irrigation water
Shading	Shade screens Coating

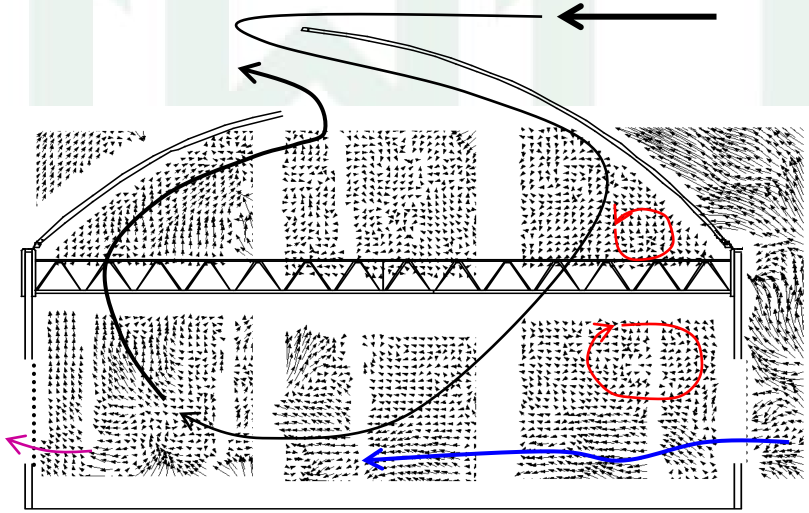
Ventilation

- Air exchange between inside and outside
- First stage of cooling
- Benefits
  - Remove heat and moisture
  - Replenish CO_2
- Air exchange rate depends on:
  - Outside climate
  - Heating/Cooling equipment
- Methods
  - Natural/passive ventilation
  - Mechanical ventilation

Natural Ventilation (NV)

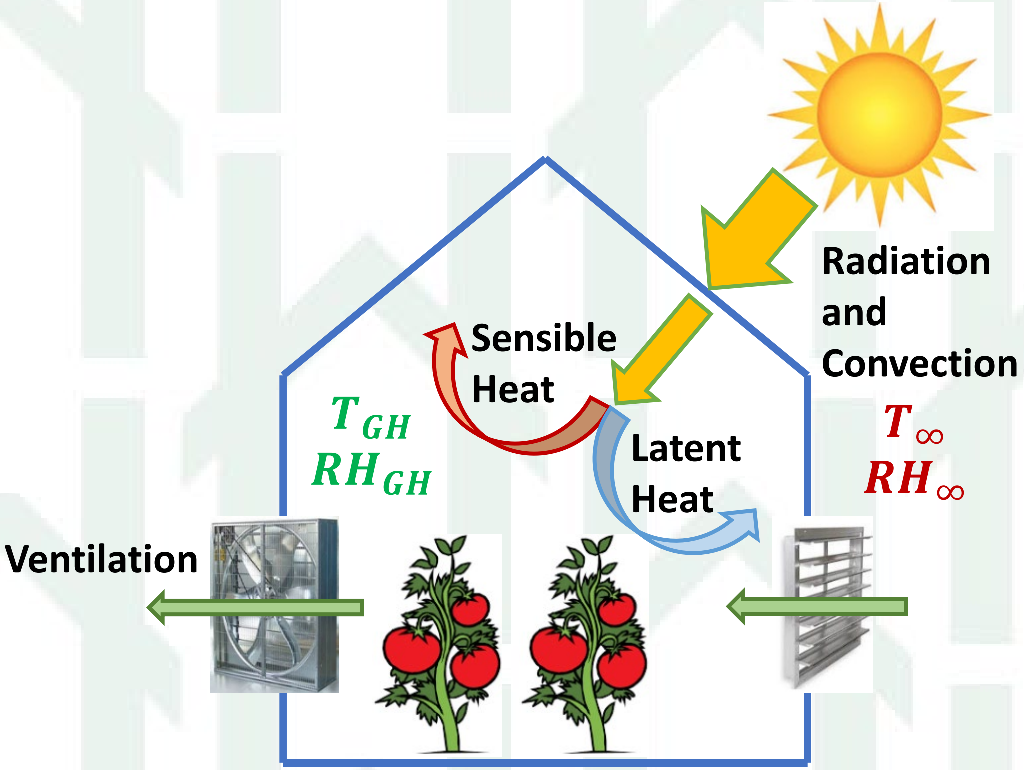
- Passively produced by **openings** in roof & walls
- Air moves in an out of GH by:
  - Buoyancy ("chimney effect")
  - Wind





Mechanical Ventilation (MV)

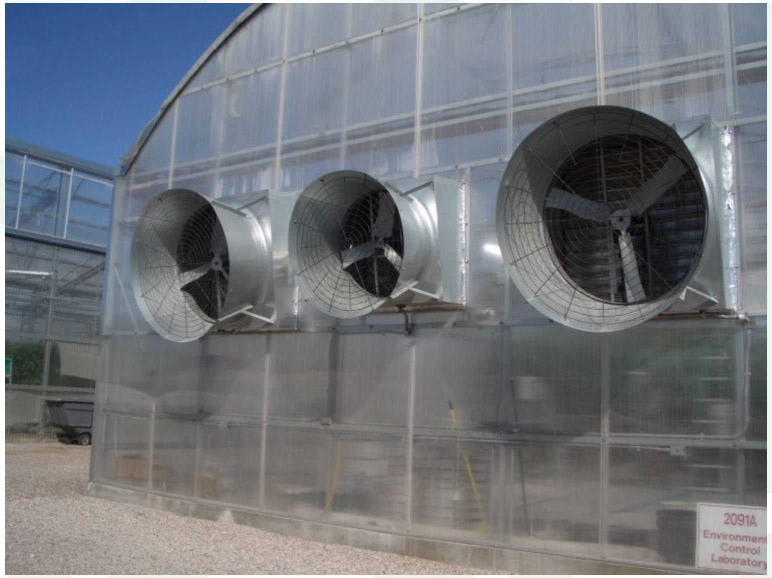
GOAL: Use fans to remove heat and moisture as quickly as it is produced/introduced into GH.



$$\text{Ventilation Rate} = \frac{\textit{Sensible Heat}}{c_1 \times \Delta T} + \frac{\textit{Latent Heat}}{c_2 \times \Delta W}$$

Mechanical Ventilation (MV)

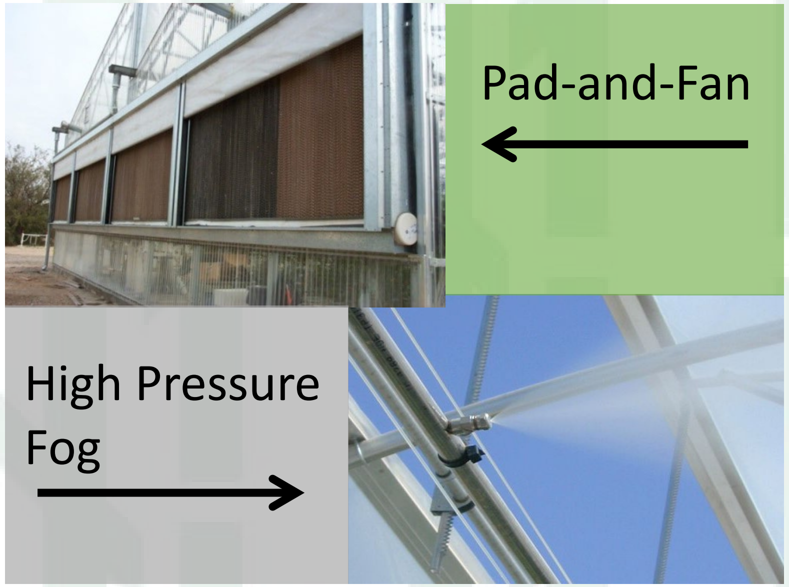
- Actively produced by **fans**
  - GH: Fans pull air through vents located at opposite end of greenhouse, along side walls, or in roof
  - WH: Fans deliver/extract air from WH using air registers at many locations



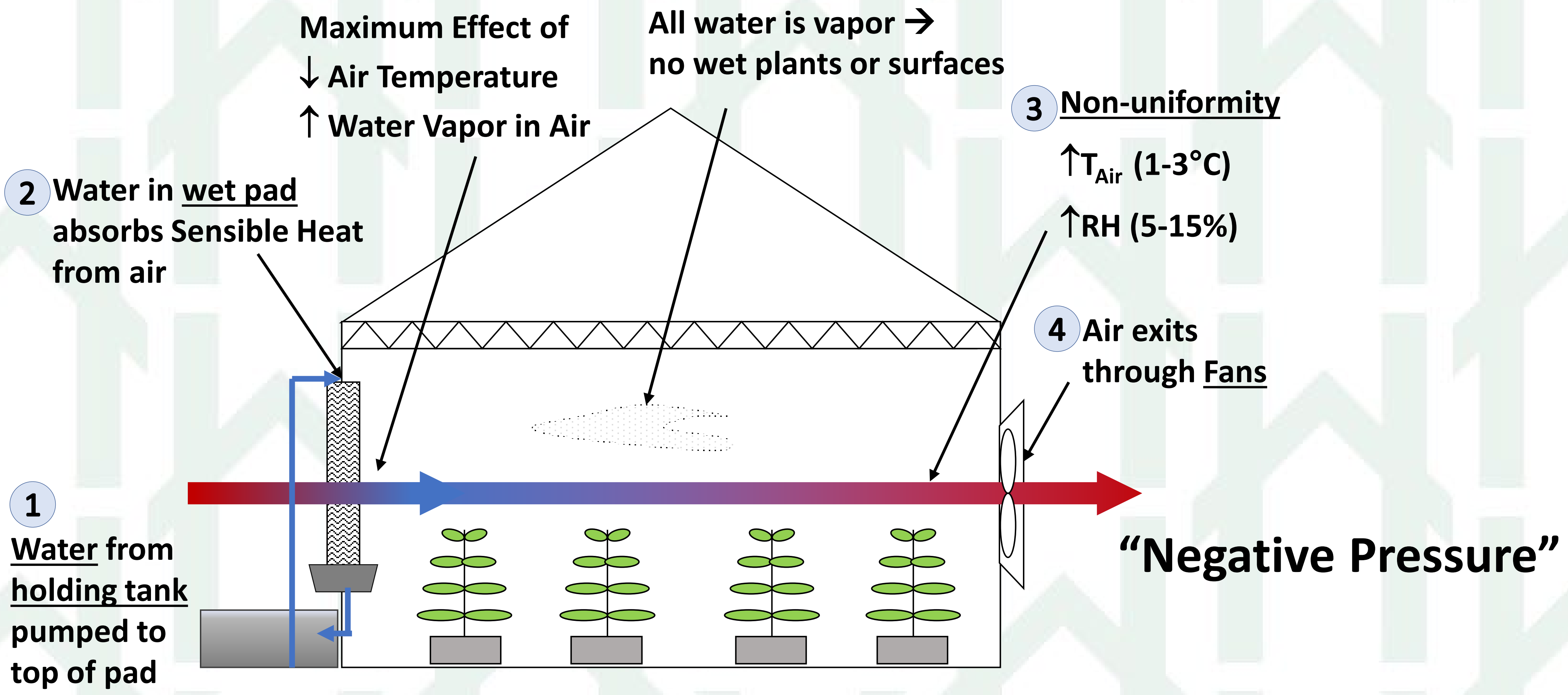
Evaporative Cooling

- Simultaneous cooling and humidification
- Most effective in hot, dry climates
  - Least effective in warm, humid climates

- Common Methods
  - Pad-and-Fan Cooling
  - High-Pressure Fog Cooling
  - ~~Low-Pressure Mist~~



Pad-and-Fan



Maximum Effect of
↓ Air Temperature
↑ Water Vapor in Air
All water is vapor →
no wet plants or surfaces
3 Non-uniformity
↑T_{Air} (1-3°C)
↑RH (5-15%)
2 Water in wet pad
absorbs Sensible Heat
from air
4 Air exits
through Fans
1
Water from
holding tank
pumped to
top of pad
"Negative Pressure"

High-Pressure Fog

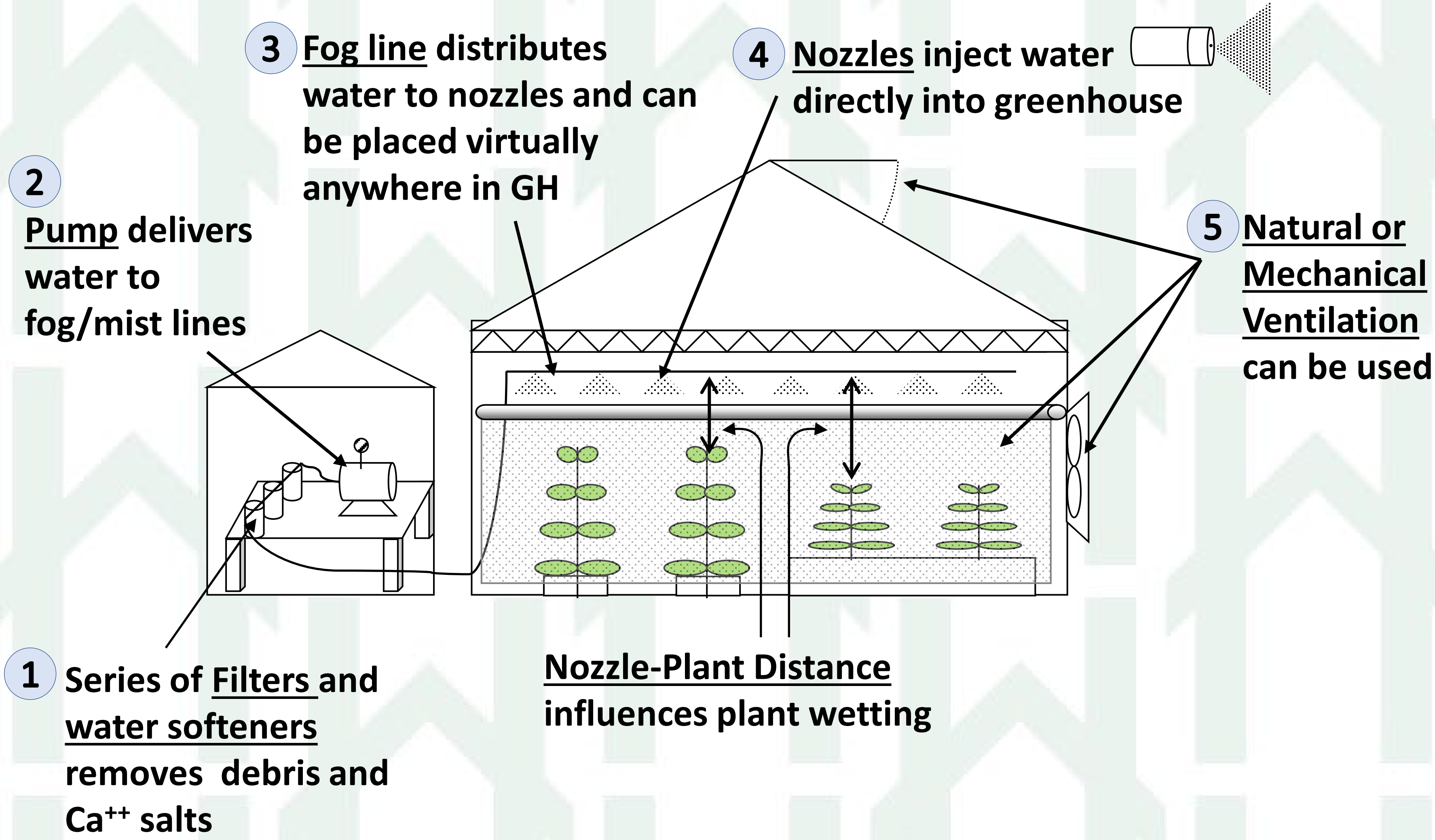
- Water delivered into the GH, where it's evaporated
- Working Pressure = 7-14 MPa (1000-2000 psi)
- Very small water droplets (5-20 μm)
  - Fast evaporation in the air

Note: Low-pressure-mist

- Working pressure < 0.4 MPa (50 psi)
- Large water droplets (> 100 μm = 0.1 mm)

  → *slow evaporation mostly on surfaces (plants, ground, etc)*

High-Pressure Fog



Evaporative Cooling: Water Use and Climate Control

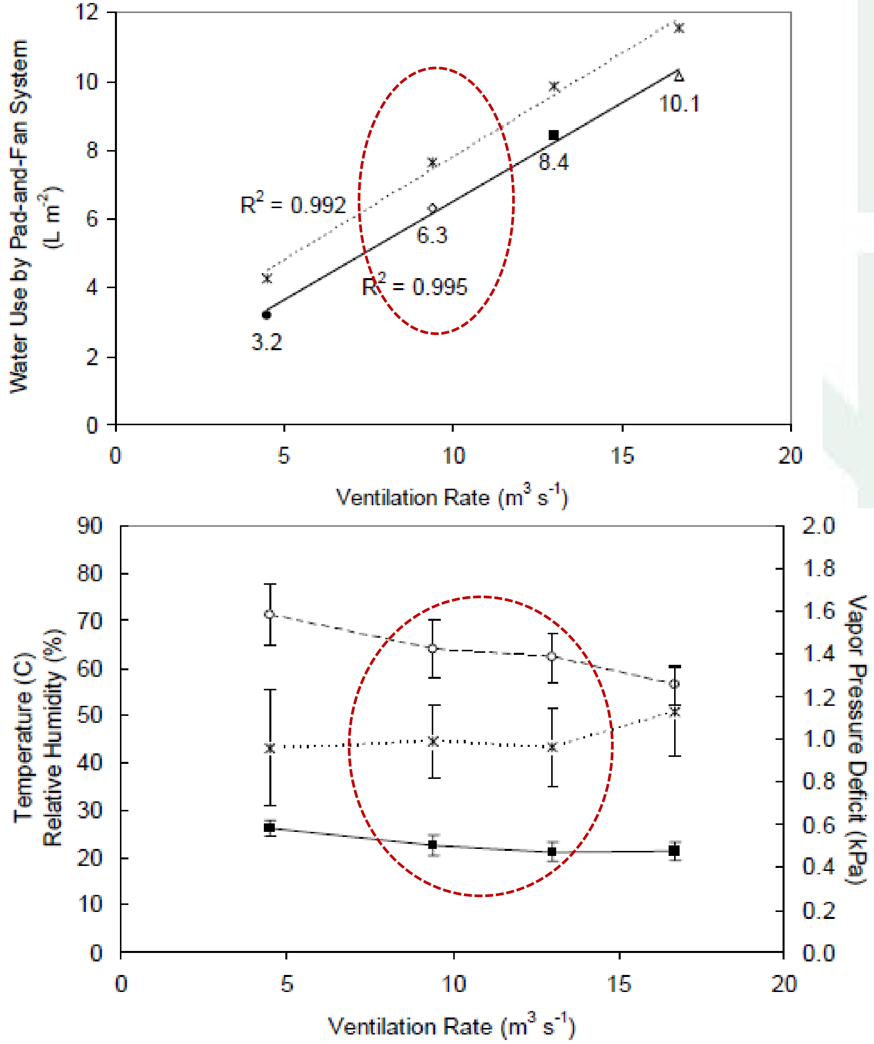


Figure 5.8 Mean daytime (08:00 – 17:00) plant zone air temperature (—■—), relative humidity (–○–), and vapor pressure deficit (···*···).

Increase Ventilation Rate
→Increase Water Use
→No Temp Improvement
→ Increased VPD

Strategic Design & Operation

- More is not always better!
- Improve Control
- Facilitate Plant Responses
- Reduce Water Use
- Reduce Energy Use

Sabeh, et al., 2007

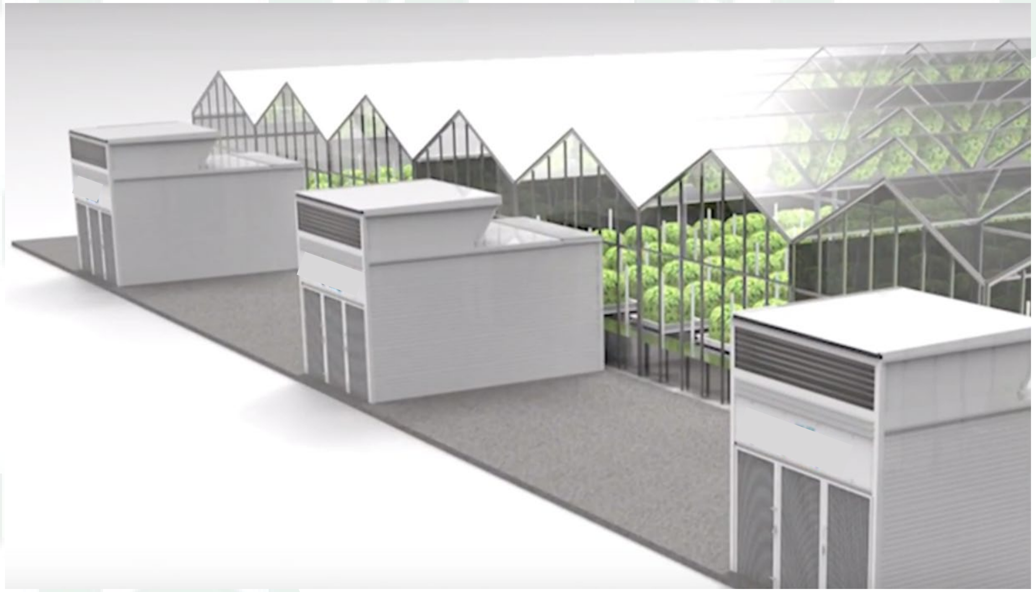
Air Conditioning

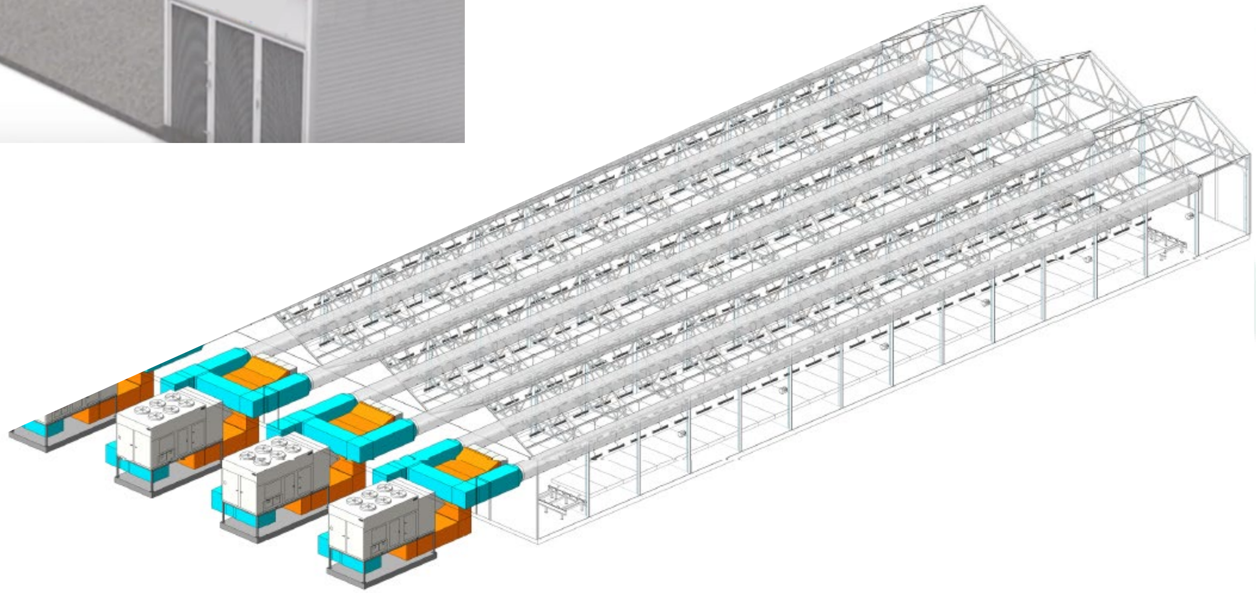
- Heat is transferred from air to cold refrigerant
- Simultaneous cooling and dehumidification
- Most effective in
  - Warehouses
  - Hot, humid climates
- Common Systems:
  - Split System: Heat pump, VRF
  - Packaged DX
  - Chiller w/AHU

<u>"DX" = Direct Expansion</u>
Heat from air transfers to refrigerant, causing it to evaporate and "expand"

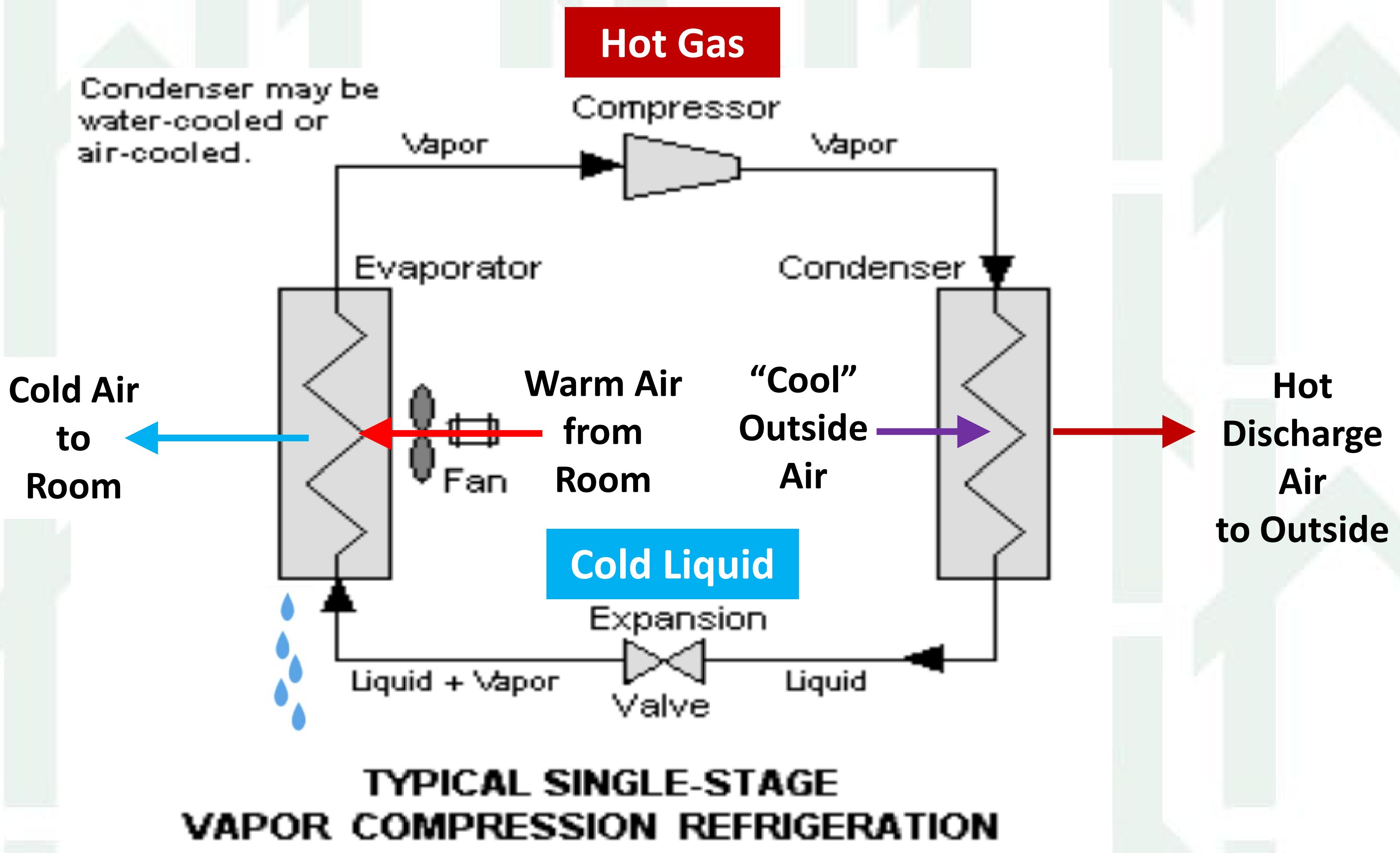
Air Conditioning – Split AC

Air Conditioning – Package DX

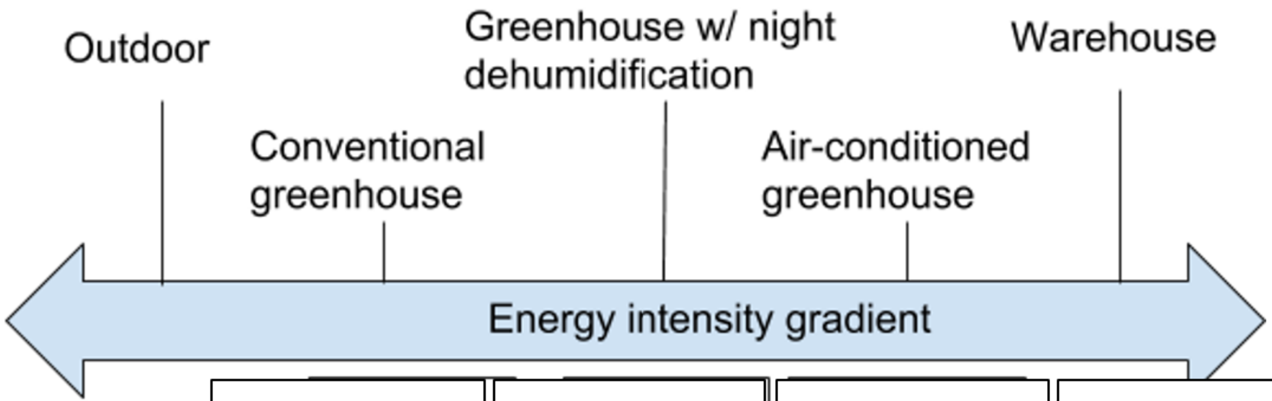




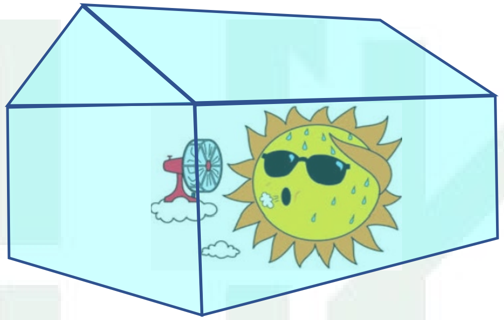
Refrigeration Cycle



Greenhouse Cooling Energy Use



10-70 kWh/sf/yr	100-200 kWh/sf/yr	200-800 kWh/sf/yr	160-500 kWh/sf/yr



Case Study – Cooling Energy Cost

Greenhouse in Oklahoma = 30x100x15 ft = 45,000 ft^3

Greenhouse w/Pad & Fan Evaporative Cooling

Airflow = 60 ACH = 45,000 CFM
Thrip Screen: ESP = 0.1 in wg
Light Traps: ESP = 0.15 in wg
Total ESP = 0.25 in wg

New Fan Size = 7500 CFM
Need 6 Fans = 45,000 CFM

Each Fan = 818 Watts
Assume 50% operation

Fan Energy = 818 W x 6 fans x 50% (8760 hr/yr)
Fan Energy = 21,500 kWh

Case Study – Cooling Energy Cost

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Assume 50% operation

Fan Energy = 818 W x 6 fans x 50% (8760 hr/yr)
Fan Energy = 21,500 kWh

Fan Energy = 21,500 kWh
x $0.10/kWh
Cost = $2,150 year

Case Study – Cooling Energy Cost

Greenhouse in Oklahoma = 30x100x15 ft = 45,000 ft^3

Greenhouse w/Air Conditioning

Air Conditioning = Cool + Dehumidification
Pkgd DX Unit w/filters

AC Capacity = 100 tons = 1,200 MBH
AC Operation = 75% duty cycle

AC Energy Use = 351.7 kW x 8760 hrs
AC Energy Use = 2,310,000 kWH

Case Study – Cooling Energy Cost

Greenhouse in Oklahoma = 30x100x15 ft = 45,000 ft^3

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Pkgd DX Unit w/filters

AC Capacity = 100 tons = 1,200 MBH

AC Operation = 75% duty cycle

AC Energy Use = 351.7 kW x 8760 hrs

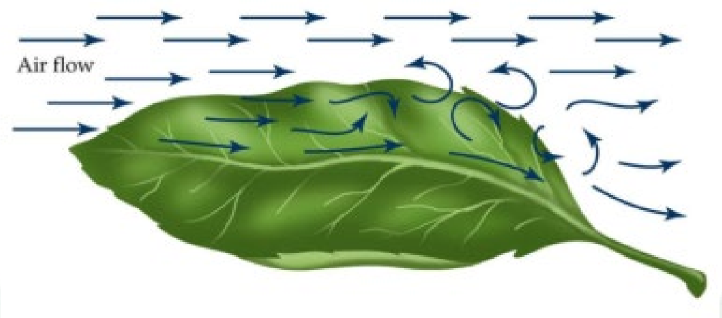
AC Energy Use = 2,310,000 kWH

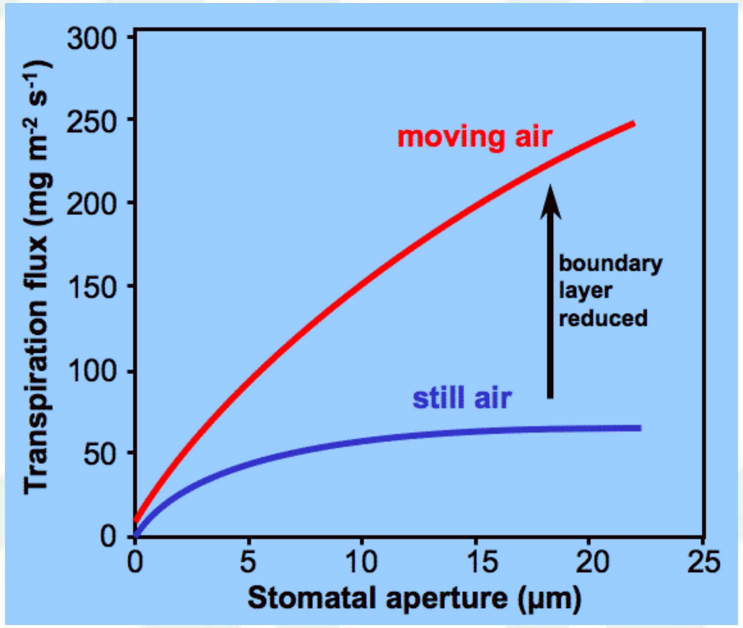
AC Energy = 2,310,000 kWh
x $0.10/kWh
Cost = $231,000 year!

Air Conditioning = 10x $$ Evaporative Cooling

Air Movement

1. Breaks up leaf boundary layer
2. Facilitates Evapotranspiration
3. Delivers CO_2
4. Eliminates waste
   - O_2, H_2O, Heat
5. Prevents condensation
6. Discourages pests





Air Movement Methods

Carbon Dioxide Enrichment

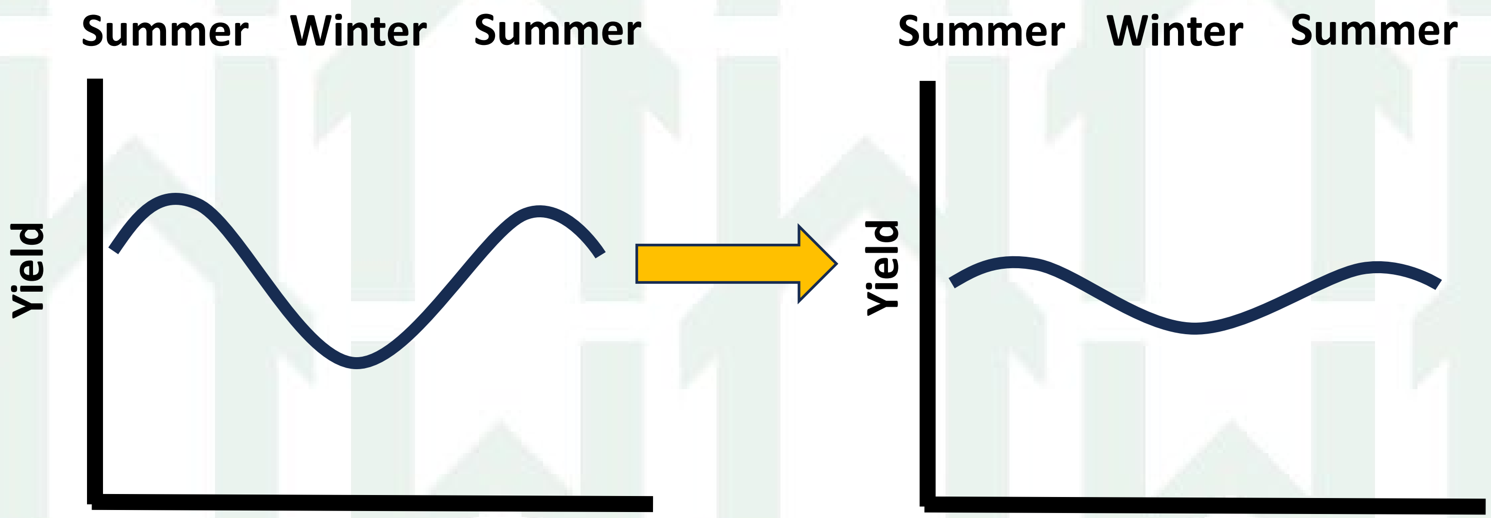
- Increase rate of photosynthesis
- Optimize for levels of light & air temperature




Efficient Operating Strategies

Efficiency = Consistency

Let's flatten the curve!



1. Lighting Management

Time of Year	Strategy	Pros	Cons
Winter	Supplemental Lighting	↑DLI ↓ Heat energy ↑ Winter Yield	↑ Lighting energy
Summer	Shading No lighting	↓ Heat stress ↓ Cooling energy ↓ Lighting energy	↓ DLI ↓ Summer Yield

2. CO_2 Management

Time of Year	Strategy	Pros	Cons
Winter	CO_2 Enrichment	↑Photosynthesis ↑ Winter Yield ↓ Heating energy	↑ CO_2 consumption
Summer	No CO_2 Enrichment	↓ Save CO_2 ↓ Cooling energy	↓ Summer Yield

Note: Summer yields and plant photosynthesis will already be high due to high sunlight levels

3. Variable Speed Fans

Time of Year	Strategy	Pros	Cons
Winter	Low fan speed	↑ Uniformity ↑ Humidity control ↓ Plant shock ↓ Fan energy ↓ Heating energy ↓ CO_2 use	↑ High cost for fans
Summer	High fan speed	↑ Heat removal	↑ Fan Energy ↑ CO_2 use

Back to our initial questions

1. Can you grow consistently year-round?

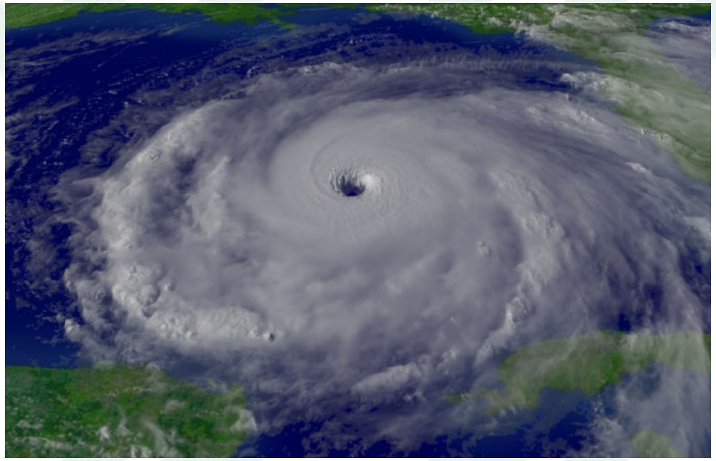
2. Are GHs more sustainable than indoor grows?

3. Are GHs cheaper than indoor grows?

4. Can you grow the same quality crop as indoor?

Greenhouse Added-Value

- Hedge Risks
  - Mother Nature
  - Market Variability
- Variability Advantage?



Prime Factors for Planning/Design

1. Crop/Product → Who's your market?
2. Location → Where's your market?
3. ROI & RUE

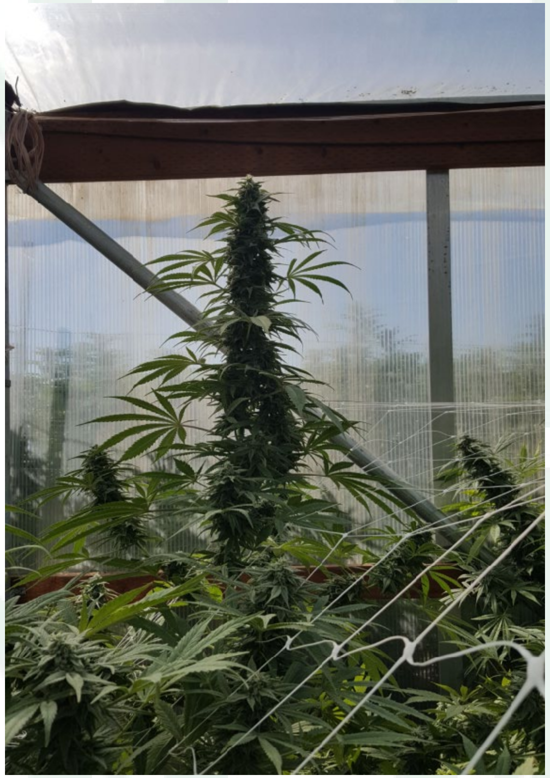
Crop/Product

- Product

Whole Sale
Extraction/Oils

↔

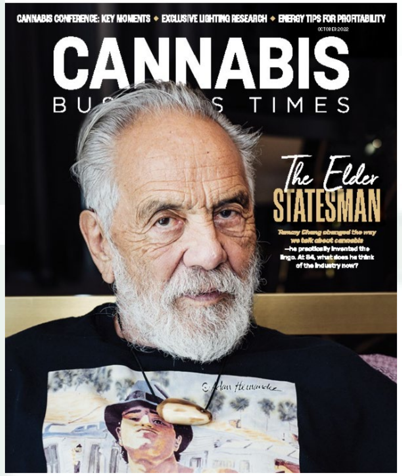
Top Shelf
Flower



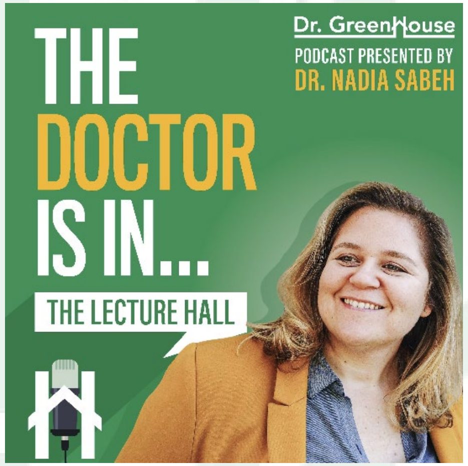
- Market
  - Direct to consumer
  - Manufacturer/processor

Learn More!

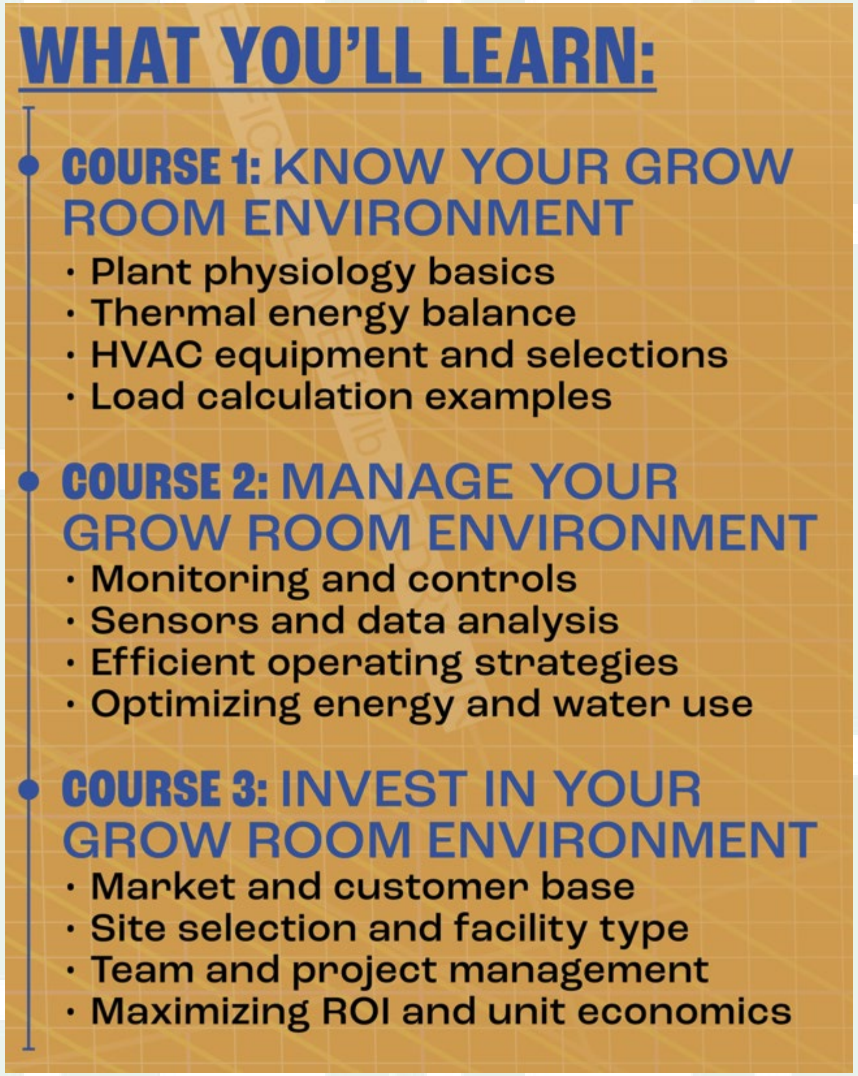
- CBT Article (Oct 2022)
  - Operating Strategies to Increase Bottom Line
  - "The Profit Denominator"



- Greenhouse Podcast Series
  - April 18, 2023: 4 Energy Efficiency Tips for GHs
  - April 25, 2023: 6 Tips for Keeping GH Cool
  - May 2, 2023: 3 GH Trends to Watch



HVAC and Controls Workshops and Classess



Thank you!

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Dr. GreenHouse