Engineering CEA Systems for a Sustainable Future: Status, Challenges, and Opportunities

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Controlled Environment Agriculture (CEA)

- Integrated science and engineering-based approach
- Establish most favorable environmental conditions for plant productivity and quality
- Optimized resources;
  - Water
  - Energy
  - Labor
  - Space
  - Capital
- Provide desired plant product or biological processes under controlled conditions.
Controlled Environment Plant Production Systems
Greenhouse Crop Production

The issues are:
energy, labor, water, product quality, marketing, food safety and to make a profit

The Challenges/Limitations:

Education / Experience
Resource [re-]utilization (energy, water, elements)
Design / Planning for current & future needs
Knowledge – IT, sensors, telepresence
Market Development
Social/Economic acceptance

(Exerted from Dr. G. Giacomelli)
CEA technology to meet the needs of the World

- Providing food and ornamental crops
- Conserving resources
- Reducing impact of agricultural production on environment

(Exerted from Dr. G. Giacomelli)
The BIG PICTURE

Production Success
Experienced and Educated Labor Force

CEA Systems

Technical Success
Engineering and Horticultural Knowledge

Economic Success
Marketing and Sales
From traditional to sustainable systems

Traditional Systems
Control the GH climate automatically

Sustainable Production Systems
Establish production instruments
- Resource conserving
- Environmentally sound
- Economically viable
- Socially supportive
- Commercially competitive
Total Areas in Major Greenhouse Production Countries in the World
Challenges of the US Greenhouse Growers

1. **Labor costs** 25.4%
2. Competition 23.0%
3. Energy costs 16.0%

Greenhouse Technology Levels in the US (High Technology)

**EuroFresh Farms, Wilcox, AZ**
- 111 ha in Wilcox, 17 ha in Snowflake, 1 ha semi-closed greenhouse in Wilcox.
- Exceeding 75 kg/m²/year tomato production, 100 Million kg tomatoes per year (220M lbs), 275,000 kg per day (600,000 lbs) [every day!]
- Glass venlo type
- Tomatoes, cucumbers

**Village Farms, Marfa, TX**
- 49 ha in Marfa, Texas, 0.6 ha semi-closed greenhouse in Marfa, 12 ha in Monahans, TX.
- Exceeding 100 kg/m²/year tomato production.
- Plastic arch type (Marfa), Glass (Monahans)
- Tomatoes

**Houweling’s, Oxnard, CA**
- 50.2 ha in US, 21 ha in Canada, 16 ha semi-closed greenhouse in Oxnard, CA.
- Glass venlo type
- Tomatoes, cucumbers

**Backyard Farms, Madison, ME**
- 16.9 ha in Maine
- Glass venlo type
- Tomatoes

**Windset Farms, N V**
- 26 ha in-construction in Santa Maria Valley, CA
- Glass venlo type
- Tomatoes, peppers, cucumbers, eggplants

**Wholesum Harvest, Amado, AZ**
- 4.85 ha semi-closed in Amado
- Glass venlo type
- Only organic tomatoes, peppers, cucumbers, eggplants etc.
Semi-closed Greenhouses: Observations/advantages/challenges

- Less use of crop protection
- Increased CO₂ for photosynthesis
- Increased yields
- Recycling/reuse of resources (i.e. water/fertilizer)
- Cooling from only below with air tubes may lead to vertical temperature and humidity gradients, lowest temperatures on fruits.
- Air tubes/air circulation demands for high energy input
- Need for sophisticated control strategies and skilled operators/workforce
- High investment cost, need for larger scale operations
Greenhouse Technologies in the US
(Low Technology)

- Most total area of single free standing greenhouses
- In terms of numbers of HTs, the Northeast and Mid-Atlantic region holds 40% of total HTs structures in the US. Around 1800 ha (based on 2007 survey 2007), is growing, and expected to grow in the next 10 years (Orzelek, 2009)
- Fresh, local food production, adaptability to urban settings
- USDA support $13M for more than 2400 farmers to install HTs
- Vegetables, Herbs, Small Fruit, Tree Fruit, Cut Flowers, Specialty Crops
- Interest in improving interior climate with low cost mechanization/automation, alternative energy systems integration, and local resources utilization

Permanent HTs

Temporary HTs

(Images credit: Dr. M. D. Orzolek)
Urban Agriculture, Rooftop Farming

Growing interest
- Food miles
- Reduced transportation and fuel use
- Local and fresh food
- Support for local jobs and local farmers
Plant Factory (Indoor Plant Production) Systems
- Minimal land use,
- Minimized water and energy use
- Fresh, pesticide-free produce regardless of climate or location, year round.

Challenges
- High energy and facility installation costs
- Cultivation technology yet to be established
- Lack of human/expert resources to operate/manage the systems
- Limited types/varieties of crops available
Sensing/understanding plant/microclimate interactions to develop energy efficient, resource conserving control/management strategies in CEA systems.
Resource savings and production quality

Combining greenhouse physics with crop physiological information

Plant Response Based Control
- Plants as “Sensors”

Big Data
- Greenhouse status
- Crop diagnostics
- Decision support
- Control actions
Microprecision Techniques

- Need?
- How much?
- When?

Action for plant’s need
Quantitative - Qualitative
Microprecision Techniques

- Speaking plant approach
- Artificial Intelligence
- Biorobotics
- Biomechatronics
IT for Greenhouse Production Management

- Greenhouse automation through multitasking sensor platforms
- Plant response based sensing/control
- Wireless sensors and actuators
- Distributed microcontrollers
- Web cameras
- Remote supervisory systems
- Remote support and troubleshooting networks

(Image courtesy of Peter Ling, Ohio State Univ.)

(Image courtesy of D. Rus, MIT)
**Sensing from single leaf**

(Hashimoto, 1979; Oosterhuis et al., 1985; Omasa et al., 1987; Seginer et al., 1992; Shimizu and Heins, 1995; Kurata and Yan, 1996; Revollon et al., 1998; ......)

**Sensing from a plant**

(Ling et al., 1995; Kurata and Yan, 1996; Murase et al., 1997, Kacira, 2000, 2002; Gu anghui and Li, 2003; ....)

**Sensing from canopy**

(Leinonen and Jones, 2004; Ushada et al., 2006; Henrewan and Murase, 2008; Story and Kacira, 2010)
Smart CEA Technologies through Advanced Sensing and Decision Support (D. Story and M. Kacira)

- Plants as “sensors” for health/growth diagnostics, determine crop needs
- Multi-sensor/sensing based approach
- Improved resource use efficiency and product quality
- Remote Expert Decision Support System Development

**Motivation**
- Excessive heat load, limited year round production
- High cooling demands
- Greenhouse climate non-uniformity

**Need**
- Modeling greenhouse and crop energy balance
- Develop advanced climate control strategies
- Water and energy savings
### Outside and Maintained Greenhouse Inside Climate

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<td>0.27-0.42 g m(^{-2}) s(^{-1})</td>
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<th>T (°C)</th>
<th>RH (%)</th>
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Outside and Maintained Greenhouse Inside Climate Difference
Analysis of Greenhouse Aerodynamics using CFD applications
(Tamimi and Kacira, 2012)
Uniformity of Greenhouse Climate under Natural ventilation Equipped with High Pressure Fogging (Cases with Side Nozzles)
Challenges and key constraints of smallholder farmers in developing countries

a) **Water** - how to generate the greatest efficiency with a very precious resource

b) **Nutrients** - without fossil-fuel-based fertilizers, how to support organic nutrient recycling within dry soils which impacts bio-degradation rates

c) **Pests, Disease and Post-Harvest** - how is the crop protected during production, and its end products stored, consumed, or marketed

d) **Power** - how is electric or thermal energy managed (provided or reduced) for reliable agricultural production

e) **Food Safety and Health Risks** - How the use of degraded or waste water use in irrigation affects food safety

f) **Communication** - how to distribute information effectively to isolated and remote communities of people with limited education

g) **Malnutrition** - how do you provide fresh and nutritious food for the children and families

h) **Female involvement** - how do you empower women in decision making processes of agricultural production from seed to market

i) **Education** - how effectively do you provide education and dissemination of knowledge, so that smallholder farmers are empowered with skills and tools to sustainably improve their income and living status and ultimately their community
Technologies for Enhancing Food Production, Resource Use Efficiencies, Environmental Friendliness within CEA
(M. Kacira, G. Giacomelli, P. Rorabaugh, C. Kubota, P. Juang, 2012-2013)

Challenges/Motivation
- Greenhouse crop production demand for resource inputs (i.e. water, fertilizers and energy), limited immediate access to these resources for sustainable food production, especially in arid and semi-arid regions.
- Growing consumer interest towards local, fresh, and safe food produce.
- Growing interest in lower cost high tunnel technology for small scale CEA food production,
- CEA crop production system must go beyond just providing higher yields, but integrate alternative energy system, appropriate technologies, control strategies and measures leading to more sustainable production, environmental friendliness, resource recycling/reuse, and be socially supportive.
Need

- Study technical and economical feasibility of an off-grid, low-cost controlled environment crop production system
- Determine resource usage/consumption (energy, water, fertilizer, labor) and production outputs (crop yield, energy production)
- Evaluate effect of plants for the energy demand and dynamics of system
- Determine limitations and capabilities of system and provide recommendations for stakeholders
High Lycopene Tomato Production and Evaluation of Oxidative Capacity in Fruit and Human Body The Tomato Feeding Study”
(C. Kubota and C. Thomson, 2005-2007)

“Small difference in maturity stage created a large difference in lycopene concentration
- Difficult to detect with human eyes, computer vision?
Applications of supplemental LED lighting in greenhouse vegetable propagation
(C. Kubota, R. Hernandez)

Engineering Challenges in LED Lighting

• Improving energy-light conversion efficiency

• Preventing the decay over time (i.e., LED life is long but light intensity decreases significantly over time.)

• Reducing the costs to develop luminaires suitable for plant lighting
Lunar Greenhouse Prototype (Phase I and II)  
(Giacomelli, Kacira, Furfaro, Patterson, Sadler)  
(TAS-I, AeroSekur, Univ. Federico II, Italy)

- Provide food (i.e. vegetarian diet),
- Revitalize atmosphere (i.e. liberate $O_2$, fix $CO_2$),
- Water recycling (via transpiration)

21 m$^3$ LGH + 2 m$^3$ HVAC  
4.3 VAC/day = 0.18 VAC/h
EDUCATION is the KEY for Success!

Challenges for Industry
• Limited number of qualified applicants despite demonstrated hiring needs
• Limited resources to educate new or retrain current employees

Challenges for Academia
• Limited resources to maintain/create effective engineering/technology intensive, high quality educational programs (95% CEA courses by Hort/Crop Science, 5% by Engineering Programs in the US)
• Identifying/retaining sufficient numbers of students, excited about engineering oriented career in CEA
• Maintaining/creating engineering/technology-oriented educational programs in CEPP
• Limited/decreasing number of institutions with active CEA engineering/technology options or programs

USDA-HEC Project: Controlled Environment Plant Production Engineering/technology Education Modules
• 40 CEA Engineering/Technology teaching modules
• Intended for online teaching
Sustainable CEA Systems and Crop Production

- Optimal use of solar energy in greenhouse domain
- Effective conversion of energy, storage and re-utilization
- Energy saving strategies
- Intelligent climate control strategies
- Improved resource use efficiency: yield per unit resource use
- Integration and increased use of non-fossil fuel resources in CEA systems
- Use of new techniques, concepts, technologies, “Smart CEA Systems”
THANK YOU