2024 Annual Report
NCERA-101 Controlled Environment Technology and Use

Project Number: NCERA-101
Project Title: Controlled Environment Technology and Use
Period Covered: 04-2023 to 04-2024
Date of This Report: May 30, 2024

2023 NCERA-101 Annual Meeting
March 23 to 26, 2024 in Des Moines, IA
Hosted by: Christopher Currey (Iowa State University) and Jonathan Frantz (Corteva)

Participants

NCERA-101 Participants List 2024 Annual Meeting

Last name	First name	Institution
Ahamed	Md Shamim	University of California, Davis
Arment	Nicole	Iowa State University
Bates	Jeffrey	UbiQD, Inc.
Bergstrom	Jordan	University of Minnesota
Bhattarai	Krishna	Texas A&M Agrilife Research
Birtell	Eva	Sparks Lab - University of Delaware
Blonquist	Mark	Apogee Instruments, Inc.
Both	A.J.	Rutgers University
Brinkman	Doug	MN Agricultural Experiment Station
Bugbee	Bruce	Utah state university
Cantor	Alex	Bright Farms
Carcamo	Henry	Free
Chung	Hanwook	Iowa State University
Costine	Blake	Aetos Systems
Craver	Joshua	Colorado State University
Crawford	Daniel	University of Florida
Currey	Christopher	Iowa State University
Da Silva	Cristiane	NCSU
Duron	Lian	Purdue University
Dzakovich	Michael	USDA-ARS
Eckels	Madigan	Utah State University
Eddy	Rob	Resource Innovation Institute
Ertle	John	PP Systems
Eylands	Nathan	University of Minnesota

Ezzo	Matt	Environmental Growth Chambers
Farinacci	Joe	BFG Supply
Feng	Iris	North Dakota State University
Fidler	Michael	Purdue University
Frantz	Jonathan	Corteva Agriscience
Gardner	Gary	University of Minnesota
Garrity	Keegan	Apogee Instruments
Gladon	Richard	Iowa State University
Gladon	Donna	Iowa State University
Gomez	Ana Sofia	Purdue University
Gomez	Celina	Purdue University
Grist	Glen	Conviron / Argus Controls
Hammad	Ahmed	Conviron / Argus Controls
Hernandez	Ricardo	NCSU
Higgins	Brendan	Auburn University
Houston	Lauren	JR Peters
Humphrey	Samson	NCSU
Imberti	David	Percival Scientific, Inc.
Imberti	Henry	Percival Scientific, Inc.
Inoue	Yuta	Cornell University
Jia	Fei	Heliospectra
Jia	Xinhua	North Dakota State University
Kanwar	Rameshwar	Iowa State University
Karimzadeh	Saeed	University of California Davis
Karlsson	Meriam	University of Alaska Fairbanks
Kennebeck	Emily	University of Delaware
Kiekhaefer	Daniel	Percival scientific, inc
Kopf	Mary Jo	LI-COR Environmental
Kramer	Hannah	Iowa State University
Kubota	Chieri	Ohio State University
Langenfeld	Noah	Utah State University
Lefsrud	Mark	Mcgill
Lewis	Nathan	Percival Scientific, Inc.
Liebing	Olivia	Iowa State University
Lim	Sungeun	Purdue University
Litvin	Alexander	ISA
Liu	Jun	Texas A&M Agrilife Research
Lopez	Roberto	Michigan State University
Lyons	Megan	Percival Scientific, Inc.

Mamrocha	Brian	Conviron / Argus Controls
Massa	Gioia	NASA Kennedy Space Center
Mattson	Neil	Cornell University
Mbacke	Khadija	Iowa State University
Mccann	Leah	Plenty Unlimited, LLC
Meng	Qingwu (William)	University of Delaware
Meyer	Hannah	Genective USA Corp
Mickens	Matthew	NASA
Mikhailova	Kristina	Cornell University
Mitchell	Cary	Purdue University
Moon	Youyoun	West Virginia University
Moosavinezhad	Seyyedmoein	NCSU
Moran	Morgan	NCSU
Morrow	Robert	Sierra Space
Morse	Justin	LLK Greenhouse Solutions
Msabila	Shem Elias	University of Delaware
Oakland	Jake	Percival Scientific, Inc.
Ogden	Andrew	University of Georgia
Orellana	Massiel	Syngenta
Osborn	Liz	LI-COR Environmental
Pauls	Robert	Bio Chambers Incorporated
Pradhan	Deepti	NC State University
Putra	Ketut	Koidra Inc
Qian	Yufei	University of California, Davis
Rahman	Md Sazan	University of New Hampshire
Ren-butcher	Yan	Rayn growing systems
Romer	Mark	Mcgill University Phytotron
Ruiz vega	Sofia	Ncsu
Runkle	Erik	Michigan State University
Schoeller	Erich	University of Georgia
Shelton	Annie	Cornell University
Shi	Xiaonan	NCSU
Short	Gregg	Greenhouse Design LLC
Soutar	Bonnie	BPQ
Spencer	Lashelle	Noetic Strategies
Spenser	Liam	Scynce LED
Talan	Matthew	Cornell University
Theroux	Marc	Bio Chambers Incorporated
Velasco	Vera	University of Toronto Mississauga

Villouta	Camilo	University of Rhode Island
Waldrop	Erin	Genective USA Corp
Walters	Kellie	University of Tennessee
Wang	Liping	University of Wyoming
Waterland	Nicole	West Virginia University
Wheeler	Raymond	NASA
Wiebe	Edward	Bio Chambers Incorporated
Williams	Brenton	OASIS Grower Solutions
Xia	Darren (Jiaqi)	Cornell University
Yelton	Melanie	Grow Big Consultants
Zhang	Ying	University of Florida

Summary of minutes of annual meeting

NCERA-101 Business Meeting Summary
Meeting started at 9:25 AM on March 24, 2024.

- Introduction and Welcoming Remarks from meeting host (Christopher Currey)
- Introduction of the NCERA-101 Executive Officers
    - Chair: Ricardo Hernandez (NCSU)
    - Chair Elect: Dr. Neil Matson (Cornell)
    - Secretary: Celina Gómez (Purdue)
- Recognition of Industry Sponsors (Christopher Currey, Ricardo Hernandez)
- NIFA Representative Report (Steven J. Thomson)
    - Urban, Indoor, and Emerging Agriculture Program (UIE) was one-shot program and has not been renewed. Developing and obtaining this program was 3.5 years in the making.
    - AFRI programs A1521, A1551 Engineering and A1541 Data Science programs have taken many CEA-related proposals, as has SBIR 8.13. A1551 and A1541, with an unprecedented increase in the number of proposals.
    - Currently waiting for the 2024 budget. Programs now send out notification of Panel Execution to all applicants indicating so.
    - The NSF Cyber-Physical Systems (CPS) updated solicitation is coming out soon, and funding level for "Small" proposals will be upped to $600K. NIFA continues its collaboration, and still has the "No-deadline" format, except for NSF's Frontier projects.
    - As of now, there is no further funding for NIFA's role in the AI Institutes. But that may change. Five NIFA-funded projects are continuing.
    - As always, NIFA is searching for volunteers to be a grant review panelist, you can enroll online through the NIFA portal or contact Steven directly: steven.j.thomson@usda.gov
- Approval of 2023 minutes by Neil Matson. Motion to approve the minutes by Mark Romer. Minutes approved unanimously.
- Announcements of other relevant conferences (All)
    - Root Health Symposium at UFL in Gainesville, FL, May 6 (https://fundraise.givesmart.com/e/nKvz5g?vid=15tnhj)
    - 2024 LightSym – Seoul, Republic of Korea May 19-22 (https://www.lightsym2024.org/)
    - Plant Molecular Farming for alternative proteins and Agbio Summit in Raleigh, NC, June 11-13 (https://plant-molecular-farming.com/)

  - ASPB meeting in Honolulu, HI June 22-26 (https://plantbiology.aspb.org/)
  - 2024 OHCEAC Annual Conference, Columbus, OH, July 17 (https://ohceac.osu.edu/ohceac_annual_conference)
  - 2024 CEAg World Conference & Expo, August, Raleigh, NC, August 26-28 (https://www.ceagworld.com/events/)
  - 2024 ASHS – Honolulu, Hawaii, FL, September 23 -27 (https://ashs.org/)
  - USDA multistate NE-2335 in conjunction with ASHS meeting in Hawaii
  - 2024 GLASE Summit, October 23-24 (https://glase.org/glase-summit-2024/)
  - CEA Summit East in Danville, VA, October 1-2 (https://indoor.ag/the-cea-summit-east/)
- Administrative Advisor's Report (Ramesh Kanwar)
  - Award nomination currently under review
  - Midterm review was well received
- Membership Report (Mark Romer)
  - This year marks the 49th annual meeting of the group
  - 3rd meeting in IA, first in 1992, only three industry members
  - Our current membership stands at 188 members (29 new members, dropped 17- net gain of 12)— Growing trend over the years.
  - We have 147 institutions from 37 US states and 12 different countries—three new states: Nevada, New Hampshire, and Wyoming.
  - We continue to have strong participation and support from our 55 industry member institutions. Their contributions support student participation, who are the future of this organization and CE research & industry.
  - Remembrance of two members who passed away in the last year: Richard Denis and Marc van Iersel

Membership Number .....March 2023 176
March 2024 188

- Additions.....29
- Deletions 17
- Net Gain (Loss).....12

Membership Composition	Institutions	Members
• Phytotrons & Controlled Environment Facilities	10	13
• University Departments, Agr. Exp. Stations	71	88
• Government Organizations & Contractors	11	15
• Industry Representatives	55	72
Total Number of Institutions / Members	**147**	**188**
Total Number of Countries	8	
Total Number of US States	37	

New Institutions:

- Auburn University, Dept. Biosystems Engineering and Dept. of Horticulture
- University of Nevada, Reno, Dept. of Agriculture, Veterinary and Rangeland Science
- University of New Hampshire, Agriculture, Nutrition, and Food System
- University of Wyoming, Plant Growth & Phenotyping Facility
- USDA-ARS Children's Nutrition Research Center
- University of Queensland, Australia, Plant Growth Facility
- Vineland Research and Innovation Centre, Ontario, Canada
- Adair Consulting
- AdeptAg

    - Grow Big CEA Consultants
    - JR Peters
    - LLK Greenhouse Solutions
    - NatureSweet Brands
    - NKOM Scientific Corporation
    - RAYN Growing Systems
    - RedSea Science and Technology Company
- Website Report (Carole Saravitz)
    - Main page is most viewed papers, GCH 3rd most viewed, although outdated, especially with regards to lighting
- Graduate Students Travel Grant Update (Ricardo Hernandez)
    - 22 awards, $500-100; from 9 universities
    - All awards funded by Marc van Iersel travel fund (https://marcvanierselfund.org/).
    - All students presented posters and lightning talks, where top three students will be recognized at the Gala dinner
    - Nine judges, testing new judging app to facilitate scoring, developed by Samson Humphrey
- Financial Report (Bruce Bugbee)
    - Better shape than ever, $23.5 K in travel funds from NCERA-101 travel fund, + surplus from 2023 meeting of $6k + MVI student travel fund of $31.5K; over $20k given in travel awards this year.
- Guidelines
    - ASABE Standards efforts (Mark Lefsrud) – Industry standards, we need to incentivize people to participate in developing standards.
    - Three focused on LED lighting systems:
        - ES-311 - S640 - Definition of Metrics of Radiation for Plant Growth. (Controlled Environment Horticulture) Applications. Published. Will be renewed. New committee created to modify and include ePAR and other definitions.
        - ES-311 - S642 Recommended Methods of Measurements and Testing for LED. Radiation Products for Plant Growth and Development. Published, undergoing a review and will need an update when S640 is updated.
        - ES-311 - X644 Performance Criteria for Optical Radiation Devices and Systems Installed for Plant Growth and Development. Initial ballot completed and being reviewed, should have second ballot shortly (summer 2024).
        - UL 4402 Ed. 1 - Indoor Air Quality in Buildings and Facilities Utilized for the Cultivation, Production and Processing of Cannabis, review deadline 2024-04-24.
        - PAFS - 30 - X653 Recommended Practice for Heating, Ventilation and Air Conditioning (HVAC), and Lighting Systems Used for Indoor Plant Growth without sunlight. Published ANSI/ASABE/ASHRAE EP 653.
        - ASABE PASF-30 and ASHRAE committee has been set up to begin a standard for HVAC for CEA space. Lead is Md Shamin Ahamed (UC Davis). If interested to be part contact him or Mark Lefsrud.
        - Other standards of interest: ANSI/UL 8800-2023 Standard for safety for horticultural lighting and equipment and systems which is a revision of ANSI/UL 8800-2021.
- Controlled environment research data sharing task force (Neil Mattson)
    - Users may be interested in submitting data to increase available CEA data which can lead to new data analytics tools; or as part of the public dissemination of data for scientific journal publication and as part of the data management plan for federal grants
    - Data can be publicly accessible, to provide real-world data to process, for data analytics
    - Uses GitHub to collect data (open source)

  - Most data submitted by OHSU, some by Cornell and Plenty
  - Data from several crops are currently online (https://ceaod.github.io/)
- Future Meetings:
  - 2025 - Leo Lobato [Karma Verde, Mexico]
  - 2026 – CEUF International meeting in Dundee Scotland, Sept. 6-9
  - Suggested moving meeting at the University of Georgia to 2027 [to be hosted by Rhuanito Ferrarezi and new members]
- Election of New Secretary
  - Executive committee nominated William Meng. Other nominations were called for, no volunteers. Ricardo moved the motion to approve William's role as Secretary.
- New Business Open Discussion
  - Excellence in Multistate Research Award (Celina Gómez, Ricardo Hernandez), changes will be made to annual report format so that its easy for highlights to be identified to include in future nominations.
  - NCERA-101 Significant Organization Award (Ricardo Hernandez)
- Passing of the Gavel
  - Ricardo Hernandez to Neil Mattson (incoming Chair)
  - Neil Mattson is our new Chair!
- **MEETING ADJOURNED**

Accomplishments

The complete station reports are available on the NCERA-101 website

https://www.controlledenvironments.org/station-reports/

Developed and tested new sensors, control systems, and instrumentation:

- The Veggie units fabricated by Sierra Space continue to be actively used to support University and Government plant research, crop production testing, and technology demonstrations on the ISS. Sierra Space also continues to support the Advanced Plant Habitat Unit on ISS, which is being regularly used for academic and government plant research.
- Sierra Space designed XROOTS with multiple independent growth chambers used in parallel to evaluate aeroponic and hydroponic nutrient and water delivery in microgravity. A reflight of XROOTS is being prepared for early 2025.
- Sierra Space completed Phase A of a NASA NRA for Development of Microgravity Food Production: Plant Watering, volume management, and novel plant research on the ISS. Phase A emphasis was on variable plant spacing. They received a Phase B award with an emphasis on soilless Water and Nutrient Delivery System integrated with Variable Plant Spacing, designed for eventual operation in the planned NASA KSC Ohalo plant growth facility.
- Sierra Space is currently "all hands on deck" for the first flight (uncrewed) of our Dream Chaser orbital vehicle to the ISS. Dream Chaser is a winged vehicle designed for soft runway landings and is currently undergoing final testing at the NASA Armstrong Test Facility in Ohio.
- CEE Lab at University of California, Davis investigated the fundamental concept of various solar technologies for energy harvesting, energy storage, and integration in CEA facilities. We also investigated the water harvesting fundamental for potential applications for water harvesting in CEA. They have also worked for precision control and monitoring of aerial and rootzone environments with advancing sensing and artificial intelligence.
- Percival Scientific, Inc. eliminated condensation issues of 30% of lid area in plant-tissue culture environments using LED lighting by implementation of uniform infrared LEDs.
- Members at Texas A&M University developed a deep learning model to detect and classify strawberries based on maturity level (mature, semi-mature, immature). A function was developed

for counting strawberries. The results showed a mean average accuracy of 95% for classification and counting strawberries without compromising precision and satisfying real-time requirements. The developed algorithm can be deployed on edge devices for autonomous monitoring in greenhouses.

- Members at Texas A&M University evaluated an integration of image analysis, data imbalance handling, and AI-assisted models were evaluated for early detection of diseases in tomato plants in a greenhouse environment. The evaluation's indicated that Generative Adversarial Networks (GANs)-based approach for resampling performed best, with an average classification accuracy of 97.69% for the target disease. The developed algorithm can be deployed on edge devices for autonomous disease monitoring and management in the greenhouses.
- Members at Texas A&M University developed an innovative, non-destructive AI-assisted approach to estimate lettuce growth parameters. The AI model showcases exceptional performance in predicting lettuce phenotypic parameters, achieving R2 values of 0.968, 0.953, 0.943, 0.906, and 0.965 for fresh weight, leaf area, dry weight, plant diameter, and plant height, respectively. Using this model, we identified that nutrient solution temperature (Temp: 30oC, Nitrogen: 150ppm) affects the fresh and dry weights.
- Research from members at Rutgers University on the ventilation efficiency of free-standing high tunnels showed there is little additional benefits of installing a roof vent opening in addition to roll-up side wall openings.

Plants and space applications:

- The VEG-05 test of dwarf tomatoes was conducted on ISS Dec. 2022-March 2023. A ground control ran through May 2023. Issues with low humidity led to drying and uneven germination and early growth. Later during growth and reproduction, plants received excess moisture, which led to flower and fruit loss. There were not enough fruit to allow astronauts to consume them, but ripe and unripe fruit along with leaf, adventitious root, and rooting pillow samples were frozen and returned to Earth for analysis.
- A test with the Advanced Plant Habitat (APH) on ISS finished in November 2021 growing cv. Espanola Improved chile (chili) peppers for 137 days. This was the longest single plant test in space to date. The crew consumed some fruit and completed surveys to assess the impacts of growing crops in space.
- As a part of collaboration between NASA and USDA (Epcot biotechnology laboratory), KSC tested plant growth promotion abilities of a fungus TC09 (*Cladosporium sphaerospermum*) on lettuce, mizuna and dwarf tomatoes in the ETCs.
- NASA completed a 1-year study of 26 cvs. of pea and bean leading to eight promising candidates for further study, nutritional and organoleptic analysis, and possible inclusion in future tests on ISS.
- NASA has completed trials using various species grown to a micro-green harvest stage (~8-14 days) to support NASA's Human Research Program. To date, over 70 varieties of microgreens have been screened.

Lighting strategies to improve crop yield, quality, nutrition and reduce energy use:

- Researchers at the University of Hawaii at Manoa conducted a study that resulted in significant differences in plant height, number of leaves per plant, stem diameter, total leaf length per plant, leaf dry weight per plant, and root dry weight of 'Koba' green onion plants using red LEDs compared to blue LEDs.
- Members at McGill University found that the differential effects of light quality and quantity are under scrutiny so that energy-efficient plant production may be optimized. This study aimed to determine the combined effects of amber (595 nm), red (635 nm), and blue (445 nm) wavelengths at different light intensities on tomato plant growth.

Plant nutrition and cultural management:

- The University of Delaware collaborated with an industry partner, Croda, Inc. and found that a calcium-mobilizing biostimulant continued to show high efficacy against tipburn in greenhouse hydroponic lettuce production while maintaining high biomass accumulation. The product was applied in the nutrient solution at varying concentrations on two lettuce cultivars grown under high daily light integrals and controlled tipburn occurrence and severity at the optimal concentration.

Outputs

- The Growing Beyond Earth™ participatory science engagement program run by Fairchild Tropical Botanic Garden currently has over 450 middle and high schools conducting research and providing data to NASA, as the program completes its seventh year. Each participating school conducts science tests in a chamber mimicking the ISS Veggie chamber, and student scientists collect data on different types of plants and horticultural conditions. Projects in the 2023-2024 school year tested different types of leafy greens or herbs, irradiated seeds, competition in shared root zones, and dynamic LED lighting strategies for crop growth.
- Since on-site work was reduced during COVID-19, our weekly seminar series for scientists and interns has gone virtual. This allows us to involve former interns and numerous external speakers.
- KSC food production team members continue to participate with university engineering design courses focused on aspects of space plant growth. University teams are helping to design or modify crop water delivery systems, robotic plant care systems, resource recovery systems, and more.
- Percival Scientific, Inc. designed a compressed air dehumidification system to hit point thresholds in seed storage environments. New ultrasonic humidification system and sizing methods to optimize vapor pressure deficits to 1kPa within controlled environments. Also, a new mushroom chamber with high degree of humidity uniformity, and high color temperature for fruiting. New dual-channel white LED platforms along with white with supplemental red for efficient Circadian response adjustment and studies. They have a patent-pending PetriClear to address condensation issues in LED experiments and are currently refining 8-color lighting design.
- Members from the Resource Innovation Institute published three industry reports to help improve resource use efficiency in CEA. They also designed a Workforce Development Strategy for the CEA Design & Construction Industry with the assistance of an Advisory Council of academics, training experts, and industry professionals representing 10 states. Lastly, they conducted 9 nationally-marketed webinars and published 6 trade magazine articles on resource efficiency topics for CEA operations.
- Members at Texas A&M University hosted the 5th Annual Conference in urban horticulture – Controlled environment conference at the Dallas Center with about 100 participants.
- Members at Rutgers University completed a project on electrostatic spraying of the nutrient solution onto rockwool growing media. The project resulted in a patent application and a peer-reviewed scientific publication.

Activities

- Project members conducted coordinated outreach events that delivered unbiased, research-based information on producing plants in controlled environments, including the 2023 Michigan Greenhouse Growers Expo (in Grand Rapids, MI), the 2023 Floriculture Research Alliance annual meeting (in Park City, UT), and a Horticultural Lighting Workshop (in East Lansing, MI).

- Members at MSU completed the fourth year of a research and outreach USDA-supported project entitled "Improving the profitability and sustainability of indoor leafy-greens production" in collaboration with colleagues at Arizona, Michigan State, Purdue, Ohio State, and the USDA-ARS. The project continues with a one year no-cost extension.
- Members at MSU completed the first and started the second year of the research and outreach project entitled "Controlled Environment Agriculture Herb Extension and Research Base: CEAHERB". This project is supported by the USDA and is in collaboration with colleagues at Iowa State, Michigan State, North Carolina State, Tennessee, Texas Tech, and the USDA-ARS.
- Members at MSU investigated the influence of red and far-red light intensity on the effect of the FR fraction (the fraction of far-red light to red and far-red light combined) in regulating growth attributes of kale and lettuce. They also investigated the influence of blue light intensity on the effect of the FR fraction in regulating various growth attributes of both crops. Plants were grown hydroponically indoors under LED lighting and controlled-environment conditions.
- Members at MSU quantified growth and subsequent flowering of seedlings of several annual bedding plant crops grown indoors under a broad range of daily light integrals under sole-source LED lighting.
- Members at MSU investigated the interactions between blue and far-red light on the growth of young culinary herbs. The morphology of sweet basil, cilantro, parsley, sage, oregano, and mint were examined with the objective of eliciting compact growth without compromising biomass accumulation. Plants were grown in a peat-based substrate indoors under LED lighting and controlled-environment conditions.
- Members at MSU quantified the influence of air and/or root-zone temperature on reducing undesirable purpling of young plants rooted under LEDs. They also investigated if reducing light intensity during callus induction would impact the purpling.
- Members at MSU investigated the influence of air temperature, photoperiod, and daily light integral on the growth, development, and photosynthesis of tropical foliage plants.
- Members at MSU investigated the influence of photoperiodic lighting on flower initiation and development of multiple specialty cut flower species in a greenhouse production environment. They also quantified the influence and interaction of vernalization temperature and duration and inductive photoperiod cycle of flowering responses.
- Members at MSU are conducting photoperiod studies for several floriculture species including bougainvillea, begonia, and dahlia.
- Percival Scientific, Inc. is researching more advanced gas control; nitrogen and ethylene monitoring for food ripening control and studies, integrating hydroponics and rootzone system into controlled environment systems, and conducting product verification studies for petriclear system.
- Members at McGill University conducted research which suggests that a high percentage of amber light (>75%) in a full-spectrum LED regimen may augment controlled environment crop production. Further research is ongoing with amber light.
- Members from Auburn University conducted aquaponics studies focused on how fish tank illumination and coupling versus decoupling affects aquaponics fish and tomato production.
- Members from Auburn University conducted studies on "poultryponics" to understand how biological treatment of the wastewater (using algae versus bacteria alone) impacts nutrient transformation and pathogen dynamics in the production of hydroponic lettuce.
- Members from Auburn University studied plant growth dynamics and nutrient status in the poultryponics system.
- Members from Auburn University studied tomato production in a split root system in order to enable growth of tomatoes on brackish water. The aim of this effort is to enable brackish water aquaponics (higher value fish) coupled to traditional vegetable production.

- Members from Auburn University are actively developing new industry collaboration with Young's Plant Farm, CEA producer of ornamentals in the Southeast.
- The University of Delaware (Project Director, PD), Arizona State University (Co-PD), and Colorado State University (Co-PD) collaborated on a research-education grant proposal and received a multi-year USDA NIFA Urban, Indoor, and Emerging Agriculture grant (titled Tailoring Hydroponic Factors to Controlled-Environment Production of Emerging Food Crops).
- Members at Texas A&M University found that blue (B) and green (G) light and temperature interactively regulate growth, morphology, physiology, and phytochemicals of two lettuce cultivars 'Rex' and 'Rouxai'.
- Members at Texas A&M University conducted a study in a greenhouse with hydroponic lettuce grown in two root zone temperatures (20 or 30 C) and three nitrogen (N) levels (75, 150, or 300 mg/L). Results showed that root zone temperature of 20 C reduced lettuce yield, regardless of the growing season, indicating that optimal root zone temperature for lettuce is higher than 20 C. High N level (300 mg/L) in summer increased lettuce yield but not in the spring, indicating interactive effect between N level and greenhouse environment.
- Members at Texas A&M University investigated the effect of different biostimulants (no application as control, Kelpak, Spectrum DS, MycoApply, and Tribus Continuum) on onion seedling growth under well-watered and drought stressed (50-60% field capacity) conditions. Results showed that all biostimulants significantly increased shoot weight, leaf area, plant height, and root weight compared to the control. Notably, Spectrum DS, MycoApply, and Kelpak specifically enhanced root morphology by increasing root length, root area, and root volume compared to the control, we conclude that the application of the investigated biostimulants shows promise for enhancing drought tolerance in onion seedlings.
- Members at Texas A&M University conducted a ten-cultivar spinach trial in a deep water culture (DWC) system with three different nutrient solutions: the original Hoagland nutrient solution, a magnesium (Mg)-enhanced Hoagland nutrient solution, and a potassium (K)-enhanced Hoagland nutrient solution. Results showed that the Mg-enhanced nutrient solution increased the relative chlorophyll content (SPAD value) in spinach leaves. However, the enhanced Mg and K nutrients did not affect the yield of spinach compared to the original Hoagland nutrient solution. Different cultivars resulted in diverse plant morphology and yield. Our results that enhancing Mg and K in nutrient solutions did not increase spinach yield, but enhancing Mg in nutrient solutions can increase the greenness of spinach leaves.
- Members at Texas A&M University conducted studies to better understand how end-of-production lighting could be optimized to improve the nutritional value of red leaf lettuce while achieving energy savings. Results indicate that blue light intensity and application duration co-regulate anthocyanin production, and sufficient anthocyanin production could only be achieved when both the threshold of blue light intensity and a minimal application duration are met. We further compared the effectiveness of different light spectra at enhancing the nutritional quality of indoor-grown lettuce and identified that ultraviolet-B and blue light treatments were significantly more effective at improve crop phytonutrients than other spectral regions within the biologically active radiation range.
- Members at Texas A&M University investigated the responses of lettuce growth and quality to sulfur supplementation in a hydroponic system. Specifically, we quantified the effects of sulfur supplementation to a commercial one-bag hydroponic fertilizer on lettuce growth and quality and identified the optimal level of S supplementation for lettuce production.
- Members at Rutgers University are continuing work on: testing lighting fixtures for horticultural applications; using life cycle assessment tools to assess the environmental impacts of switching

from high-pressure sodium lighting to LED lighting; evaluating hydroponic lettuce production in an NFT system; and evaluating use of agrivoltaics at three university research farms across New Jersey.

- PP Systems webinar series enters its 5th year, with 10 total publicly available webinars planned for 2024. Webinar topics share an underlying reliance on methods including leaf chlorophyll fluorescence or gas exchange of leaves or soils.
- Members from Auburn University are leading a USDA-NIFA SAS project, "Reimagining controlled environment agriculture in a low carbon world." $9.95 million.

Milestones

- Sierra Space's applications group is still focused on Propulsion and Environmental Systems (including plant payloads), and continues to operate in our facilities in Madison, Middleton, and Baraboo Wisconsin. We collaborate heavily with NASA Kennedy Space Center for our plants in space projects.
- Percival has made plans to transition to keep up with the new regulations in refrigerants in the industry. These plans have hard deadlines in the industry at the beginning of 2025 and 2026.
- Members from the Resource Innovation Institute, in partnership with Berkeley Lab (LBNL, Berkeley, California), secured $2 million in funding from the U.S. Department of Energy. Project Title: 'Leveraging Investments to Accelerate CEA Efficiency and Decarbonization at Scale.' Project duration: 2 years.
- Members at Auburn University completed greenhouse renovations and has begun side-by-side greenhouse trials in which a traditional tomato production approach is compared to a seasonal rotation of lettuce and tomatoes. The latter is expected to save energy and enable summer production in a hot/humid climate but at the expense of produce availability.
- Members at the University of Delaware led a successful renewal of the multistate NE-2335 (formerly NE-1835, Resource Optimization in Controlled Environment Agriculture) project that will continue to benefit the controlled-environment agriculture industry. The University of Delaware also organized the in-person NE-1835 annual meeting on July 31, 2023 in Orlando, FL, where members discussed collaborative efforts and shared project progress.
- PP Systems developed and tested a new Arabidopsis whole-plant chamber for gas exchange studies in 2023-2024. Ongoing testing is planned for Q2 2024 in collaboration with clients examining Arabidopsis physiology.

Impact statements

- Sierra Space continues to develop environmental control technologies for space-based biological and physical-chemical life support systems, technologies that may have applications for terrestrial environmental control systems.
- The research outcomes from the CEE Lab at University of California, Davis evaluating solar cell technology development will impact future research and technology adaptation for energy harvesting in greenhouses. The water harvesting research will enhance the circular economy concept by re-circulating the water within the CEA systems. The precision control and monitoring system will help reduce water and nutrient waste in hydroponic production. Studying plant physiology and breeding for watercress will create a new dimension for growing medicinal and high-value crops in indoor facilities like vertical farming.
- KSC's space crop production research group has developed a list of knowledge gaps that has been vetted and approved with different NASA stakeholders. To enable partnership and collaboration on the challenges in controlled environment crop production we have been sharing our gaps list and having discussions with other government agencies, members of academia, and relevant

industry professionals. The challenges that we face, while unique, have many intersections or areas of synergy with various sectors including agriculture automation and robotics, industrial sanitization, vertical farming, fluid and gas handling, modelling, sustainability and circular economy research, and greenhouse agriculture.

- The Michigan Greenhouse Growers Expo, Electronic Grower Resources Online, OptimIA, and The Floriculture Research Alliance meetings delivered unbiased, research-based information to over 3,000 greenhouse growers, plus additional growers and marketers of vegetable and fruit crops.
- Our research investigating the influence of light intensity on far-red light responses of leafy greens grown indoors provides insights into how these light dimensions regulate the harvestable yield and crop quality attributes. Information can be used by commercial vertical farmers who seek to utilize far-red light to promote crop growth.
- At least a moderate daily light integral for floriculture seedlings can improve growth and subsequent flowering of young plants. Information can be used to explore the economics of increasing light intensity considering capital and operational costs for lighting and benefits of shortened crop production cycles.
- Our lighting research with culinary herb transplants provides insights on how blue and far-red light can be used to regulate growth characteristics and increase quality. This information can be used by commercial growers in controlled environments to improve the quality of young culinary herbs.
- An increased air and root-zone temperature can be utilized to reduce undesirable purple pigmentation during rooting of herbaceous shoot-tip cuttings under LEDs.
- Photoperiods ≤16 h and daily light integrals between 4 to 8 mol·m–2·d–1 are sufficient to produce most foliage plants in controlled environments. Therefore, commercial growers in temperate climate can select crops that have lower optimum temperatures for leaf development to reduce energy costs and be competitive with growers located in other regions.
- Providing photoperiods that promote vegetative and reproductive growth can reduce production time and increase the quality and yield of specialty cut flowers. Additionally, labor savings can be achieved by quantifying the minimum number of days required for flower bud initiation under inductive photoperiods.
- Information gathered on the impact of photoperiod on growth and flowering of popular floriculture crops can be used by commercial growers to schedule plants more precisely for specific market dates and for minimizing production time.
- Percival has been involved in the ASABE X642.2 panel to help quantify lighting uniformity regulations. We've also been involved with the search for new viable refrigerant to meet new EPA energy efficiency and carbon guidelines. Improvement in humidification technology has been a central concern, with new humidification and dehumidification deisgns. This is important for seed storage and mycology research. Members at Percival have helped pioneer new hydroponics and root research into controlled environment chambers along with verification studies to improve and help eliminate condensation in plant tissue cultures.
- Members at McGill University found that the use of amber light (595 nm) has had a major impact on the growth and development of all plant species we have tested and we hope that other will begin to use this promising wavelength.
- Members at Auburn University showed that grow bed sludge is an important reservoir for micronutrients that are often deficient in aquaponics systems e.g. iron, manganese. This allowed plants to take up higher levels of several key micronutrients in coupled systems versus decoupled due to higher sludge deposition in the former. However, sludge deposition needs to be carefully managed via engineered systems so that excess sludge does not contribute to root asphyxiation. They also proved that poultry slaughterhouse wastewater can be an effective source of irrigation water for hydroponic lettuce so long as deficient nutrients (mainly micronutrients) are supplemented. Lastly, their research shows promise for growing vegetables at 10 ppt salinity in split root vegetable production enables a move toward brackish water aquaponics. This change

allows for the cultivation of higher value fish while still enabling vegetable production a potential game changer for the economics of aquaponics systems.

- Tipburn of lettuce is a major crop physiological disorder that severely affects crop quality and leads to economic losses in the controlled-environment agriculture industry. The collaboration between the University of Delaware and Croda, Inc. has identified the optimal concentration of a chemical biostimulant as an effective solution to decrease the lettuce tipburn rating by 88% without affecting yield in greenhouse conditions. This product thus has potential for wider industry adoption to enhance crop quality and harvestable yield.
- The deployment of AI-based computer vision models for strawberries developed by members from Texas A&M University could improve the performance, efficiency, and remote interactivity of autonomous yield estimation and robotic harvesting operations, reducing labor requirements and production costs. AI-assisted computer vision-based solutions in combination with crop growth models could assist growers in decision-making for optimizing management processes for indoor strawberry production, improving resource use efficiency. Further, the developed AI-assisted predictive analytics could optimize resource usage, reducing costs and improving the sustainability of the US greenhouse industry. The AI-based crop growth monitoring approach holds promise for efficient data aggregation from multiple sensors and predictive analytics to assist growers in decision-making for resource optimization.
- The Phytotron continues to play a vital role in supporting the NCSU campus community and large, as well as small companies in the NC Research Triangle Park area. The recent addition of growth facilities in the Plant Sciences Building has more than doubled the available controlled environment space on the NCSU campus, and has significantly enhanced the biocontainment facilities and growth space resources.
- Findings from efforts focused on energy conservation and crop lighting led by members at Rutgers University have been summarized and delivered to local and regional audiences. It is estimated that this information has led to proper designs of controlled environment plant production facilities and to updated operational strategies that saved an average sized (1-acre) business a total of $25,000 in operating and maintenance costs annually. Greenhouse growers who implemented the information resulting from our research and outreach materials have been able to realize energy savings between 5 and 30%.

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