NE1835: Resource Optimization in Controlled Environment Agriculture

Renewal Proposal (2023)

Participants

The team members represent multi-institutional and interdisciplinary collaborations. Our members include the following representatives for three main objectives:

Administrative Advisor: Adel Shirmohammadi

Objective 1. To optimize environmental management and control and reduce energy use for high-quality greenhouse and indoor crop production.

- *Specific objective 1.1.* Develop crop-specific guidelines for light quantity and quality in both supplemental and sole-source lighting applications.
- *Specific objective 1.2.* Investigate the conversion efficiency of electric light sources used for controlled environment crop production.
- *Specific objective 1.3.* Investigate environmental control strategies that incorporate artificial intelligence techniques.
- *Specific objective 1.4.* Investigate wavelength selective greenhouse coverings and CEAgrivoltaics applications for environmental controls and reduced resource use.
- *Specific objective 1.5.* Co-optimization of environmental variables and enhancing resource use efficiency in indoor crop production.

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Meriam Karlsson (University of Alaska Fairbanks)
A.J. Both (Rutgers University)
Roberto Lopez (Michigan State University)
Murat Kacira (University of Arizona)

Objective 2. To improve root-zone management of biotic and abiotic factors for high-quality greenhouse and indoor crop production.

- *Specific objective 2.1.* Select new crops that may be grown all year round in soilless substrates and water culture or using novel production techniques.
- *Specific objective 2.2.* Improve the efficacy of organic fertilizer for hydroponic crop production using beneficial microorganisms and controlling rootzone environments (e.g., temperature, dissolved oxygen, and pH).

- *Specific objective 2.3.* Develop aquaponic production strategies that optimize plant productivity while improving nutrient use efficiency (e.g., decoupled aquaponics and aerobic/anaerobic digestion of fish waste solids).

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Murat Kacira (University of Arizona

Objective 3. To train growers and students on new controlled-environment production and engineering knowledge.

- *Specific objective 3.1.* Develop and offer an online class in scouting for insects and diseases in controlled environment agriculture.
- *Specific objective 3.2.* Develop and share curricula for undergraduate and graduate courses in hydroponics and soilless crop production and controlled environment engineering applications for a new program in Agricultural and Environment Technology at UC Davis.
- *Specific objective 3.3.* Develop Scholarship of Teaching and Learning (SoTL) projects in CEA with university undergraduate students.
- *Specific objective 3.4.* Develop a hydroponics textbook that can be used for CEA industry members and for classroom use with contributions by many other team members.
- *Specific objective 3.5.* Develop a hydroponic training course for growers and organize an annual conference on urban agriculture - controlled environment.

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Statement of Issues

Objective 1.

Centralized open-field vegetable production suffers from low productivity, foodborne pathogens, extreme weather patterns, and seasonal disruptions. As an alternative, greenhouse and indoor vertical farming is emerging to meet consumers' demand for safe, local, fresh, and nutritious vegetables all year round. However, this industry is limited by its high energy use, which is among the highest input costs for controlled environment agriculture (CEA, including greenhouses and vertical farms). Energy use for plant lighting, temperature control, and dehumidification is also associated with the largest share of carbon emissions from indoor farms. A range of energy-efficient technologies are available (LED lighting and smart climate control); however, successful adoption requires greater knowledge of complex plant interactions with the growing environment.

Objective 2.

Hydroponic production, either nutrient solution or soilless substrate-based, is a preferred method for crop production under controlled environment like greenhouses and indoor farms. Hydroponics provides an opportunity to control the physical, chemical, and biological environment of the root zone. Physical and chemical environmental factors of root zone include nutrient composition (recipe) and concentration (electrical conductivity, EC), pH, temperature, and dissolved oxygen concentration. The biological factors are types of microorganisms (that is, microbiome) and their population. Under controlled environment in hydroponics, the microbiome in the root zone is completely different from that in soil rhizosphere.

Root zone temperature can influence plant growth and development. Greenhouse producers have been using root zone heating for decades by regulating media temperature during propagation and production of annual bedding plants and vegetable transplants. For solution-based hydroponics, root zone temperatures can be controlled through chilling and heating the nutrient reservoirs (Hooks et al., 2022; Miller et al., 2020; Sakamoto et al., 2015). The effect of root zone cooling and heating depends on air temperature and crops. However, available research-based information is limited for high-value leafy greens and culinary herbs.

As the demand for organic produce increases, interest in growing organic food crops under controlled environment using hydroponics is increasing as well. Nutrient management is more challenging with organic nutrient sources than inorganic fertilizers since organic nutrient sources often have imbalanced nutrient contents, high salinity and can introduce toxic pollutants and infectious agents and can decrease dissolved oxygen (Bergstrand et al., 2020; Kano et al., 2011; Williams, 2014). In addition, in organic fertilizer, many nutrients bound to organic substances are not immediately available for plant uptake and require microbially mediated mineralization processes (Bergstrand et al., 2020; Williams, 2014). However, current hydroponic rootzone environments are optimized principally for using inorganic fertilizer, and a significant knowledge gap exists regarding how biotic and abiotic factors of rootzone environment affect the efficacy of organic fertilizer for hydroponic crop production.

In recent years, application of bioproducts or plant biostimulants (PB) has gained recognition as a sustainable approach to boost plant growth and development under normal or stressed conditions (Askari-Khorasgani et al., 2019; Del Buono, 2021; Massa et al., 2017). PBs can be derived from a wide variety of materials: beneficial fungi such as arbuscular mycorrhizal fungi (AMF), beneficial bacteria such as plant growth-promoting rhizobacteria (PGPR), protein hydrolysate, humic substances, seaweed extract, and others (Del Buono, 2021; Shahrajabian et al., 2021). Thus, the effect of PBs largely depends on the type of PB. Few studies have been conducted to assess the efficacy of various PBs for (organic) crop production under controlled environments.

Aquaponics is a combination of aquaculture and hydroponics where fish waste is used as plant fertilizer and plants filter the water for fish. These production methods are land-use efficient and lend themselves well to urban production and to school science and agriculture classes. In the U.S., there are 5,350 aquaculture farms producing $1.8 billion wholesale annually (USDA, 2017). Aquaponics is an emerging industry, especially for urban agriculture.

Objective 3.

Controlled Environment Agriculture (CEA) is a rapidly changing field with high levels of technology. Growers and students working in CEA must understand topics including greenhouse engineering, irrigation and fertilization, business management and economics. Just in the past five to ten years, the tools and technology used in CEA have expanded to include an increased focus on LED lighting and other energy efficient technologies, hydroponic production of food, and improved sustainability of irrigation and fertilization practices. CEA technology will continue to change and evolve, making it critical to provide up to date, research-based training for growers. Highly skilled undergraduate and graduate students are needed to work in CEA; there are often more positions for graduates in this field than students to fill those positions. Our group is well positioned to train the next generation of growers and engineers as well as to connect students and the industry.

Since technology changes rapidly in this area, there is a strong need for research-based review articles and books on this topic. Currently, there are no student or grower-oriented books or review articles on the topic of hydroponics, which is a rapidly growing area of CEA. A hydroponics book would support the development of undergraduate and graduate hydroponic classes, which many members of our group either have developed or are planning to develop.

Justification

Objective 1.

The photon spectrum and intensity influence photosynthesis, plant shape, and accumulation of mineral nutrients. Light use efficiency of indoor crops also depends on other environmental factors (e.g., temperature, humidity, and carbon dioxide concentration) and cultural factors (e.g., nutrient solution concentration and composition). Therefore, optimizing the light environment based on key environmental and cultural factors has the potential to improve crop growth and nutritional value while saving electrical costs.

Optimal control of the environment in plant production facilities is a complex task due to the multiple interactions of the parameters involved. Traditional environment controls rely on sensor feedback from aerial or rootzone environment without information and data from crop growth as well as an approach considering entire production system in decision making. Integration of artificial intelligence (AI) can assist growers in making more logical, data-driven, site-specific management decisions which influence crop productivity, quality, as well as use of labor and other resources. An AI framework consists of models, controllers, and real-time data, that combined with domain knowledge can optimize decisions for selected outcomes (e.g., profitability, resource use efficiency).

Objective 2.

Traditional food crops grown in greenhouses include tomatoes, peppers, eggplant, strawberries, leafy greens, and culinary herbs. Additional novel food crops will be explored to find the high-yielding and profitable crops in greenhouse and indoor hydroponic systems to justify the high crop production cost in indoors.

Realizing year-round production under controlled environment is economically important to provide constant supply of fresh produce and increase the efficiency of the facility use. Greenhouse hydroponic crop production is energy intensive. In hot summers in southern region, cooling the air temperature of a greenhouse to optimal temperatures for many cool-season leafy greens and herbs is challenging. In cold winters, heating the entire greenhouse to the optimal level is costly. To reduce energy cost, root zone temperature control under suboptimal air temperature may be a solution. Quantifying the interaction between air and nutrient solution (root zone) temperatures is crucial to optimize crop yield, nutritional quality, and post-harvest longevity. The lack of this information limits the full utilization of the major advantage of controlled environments, which is the ability to manipulate the production environment. Consequently, there are significant gaps in economic feasibility, and the potential to provide high-quality, flavorful food to people from all socioeconomic backgrounds is diminished.

Greenhouse gas emissions associated with chemical fertilizer production, the global phosphorus shortage, and soil and water pollution caused by over application and mismanagement have all been recognized as severe threats to sustainable food production (Nosheen et al., 2021; Oelkers and Valsami-Jones, 2008). In addition, recent inorganic fertilizer shortage raised fears of a global food crisis. The use of organic materials as fertilizers has multiple advantages, such as recycling nutrients, supplying beneficial organic biostimulants, and decreasing the demand for mined minerals (Bergstrand et al., 2020).

Organic farming is one of the fastest growing segments in the U.S. agriculture. Increasing organically grown fresh produce such as fruiting vegetables, leafy greens and herbs under controlled environment is essential. Therefore, information on how to manage organic fertilizers in soilless substrate and organic hydroponics is urgently needed. In addition, the demand for organic seedlings for open field production far exceeds the supply. Controlled environment is an ideal facility for producing organic seedlings and transplants. Research-based information on how to best utilize available organic fertilizers amended with PBs to produce quality transplants will reduce transplant shock, and thus economic losses, and increase transplant tolerance to biotic and abiotic stresses after transplanting. Therefore, it is imperative to evaluate the effectiveness of PB products in tandem with organic fertilizers with optimal application rates and timings to organic farmers/stakeholders.

Aquaponics is one of the most popular systems for urban agriculture and for science classes in high schools and agriculture colleges. Although aquaponics concept is not new, there are many areas that need more research work. Cornell University research will address issues faced by aquaculture and aquaponics operators: the large volumes of solid waste that must be frequently removed and cleaned from their systems.

Objective 3.

Our group includes greenhouse engineers, horticulturists, and economists working in CEA. We are well suited to provide education and training on a broad range of topics. Many members of our team provide education in CEA through undergraduate instruction, mentoring of undergraduate and/or graduate students working on research projects, or Extension programming with CEA growers. The collaborative nature of our group allows us to broaden our programming so that our individual efforts coalesce for greater regional and national impact.

Related, Current, and Previous Work

Objective 1.

Previously, researchers at Michigan State University and Iowa State University have quantified the effects of air temperature on growth and development of 16 species and cultivars of culinary herbs determining the base and optimum temperatures for node appearance and fresh mass accumulation (Walters and Currey, 2019; Walters and Lopez, 2021). Additionally, the influence of air temperature was quantified on basil volatile compound concentration and consumer preference. For example, increasing air temperature from 23 to 36 °C increased basil volatile compounds but did not influence consumer sensory preference (Walters and Lopez, 2022).

Previous research by team members has determined the energy efficacy of horticulture lighting fixtures (NJ) and plant responses to light intensity (OH) and spectrum for specific plants and applications (DE and NY). Adjusting the lighting strategy at the end of the crop cycle can also impact growth and nutritional quality (TX), though more information is needed on specific crop systems, nutritional assays, and consumer sensory evaluation. Team members have also begun to explore the interaction between environmental factors such as light and carbon dioxide (NY) and temperature (TX).

Previous work by team members has sought to develop efficient control strategies for airflow, light, carbon dioxide, and dehumidification (AZ, NY, CA), however current control strategies often focus on discrete actions (e.g., lighting control, irrigation control), without being able to determine an optimized strategy for the entire production system. New approaches including artificial intelligence are required to develop integrated and optimal control strategies.

Objective 2.

Researchers at Arizona State University evaluated fish-based organic fertilizer and liquid food waste anaerobic digestate for soilless cultivation of lettuce and tomato transplants compared to commercially available chemical fertilizer. At the same total nitrogen concentration, lettuce ‘Cherokee’ seedlings had 75% less shoot fresh weight and 64% less dry weight under organic fertilizers, regardless of organic fertilizer types, than chemical fertilizer. Similarly, tomato ‘Red Robins’ seedlings grown with organic fertilizers had one fewer leaf, 36% smaller stem diameter, 40% shorter stem length, and 75% or 67% less shoot fresh or dry weight, respectively, compared to seedlings grown with chemical fertilizer. In another study, we investigated if using microbial biostimulants and supplementing dissolved oxygen, can improve nutrient availability, plant nutrient uptake, and thus, plant growth under organic fertilization. We identified applying arbuscular mycorrhizal fungi *Rhizophagus intraradices* every two days increases shoot fresh weight of lettuce ‘Cherokee’ by 30-98% and ‘Rex’ by 5-85% compared to un-inoculated controls under organic fertilization. In addition, supplementing oxygen to the hydroponic nutrient solution made with an organic fertilizer increased dissolved oxygen from 1.0 ppm to 5.5 ppm and promoted both shoot and root growth in lettuce ‘Cherokee’ and ‘Rex’.

Currently,an ongoing multi-state project (TX, UT) determines the efficacy of different kinds of commercially available PB products on onion and watermelon seedlings, the optimal application rates and methods, and the carry-over effects of PBs applied during seedling stage on the subsequent growth in the field. In addition, TX team is conducting research on organic fertilizers and management and determining the efficacy of various biostimulants on organic seedling production under controlled environment conditions.

Cornell University has an ongoing project in aquaponics research and extension to address issues faced by aquaculture and aquaponics operators. In preliminary research, we have developed and tested a low-cost aerobic digestion method to turn most of the solid waste into a liquid organic fertilizer. More work is needed to optimize the digestion system and we will determine the impact of temperature, residency time, and waste source on the resulting fertilizer and crop performance.

Objective 3.

Over the years, members of this project have collaborated formally and informally in many educational programs. Many of our members have partial extension appointments and organize annual greenhouse workshops and short courses in AZ, CT, IA, KS, NJ, NY, and OH. In all of these instances, we invite members from other stations to participate as speakers. We also have several members who teach controlled environment agriculture, hydroponics, sensors, controls, and/or greenhouse management to undergraduate and graduate students in CA, CO, KS, ME, TX, FL, NJ, AZ. Our collaboration makes it easier to provide up-to-date information on new topics as well as new approaches to instruction and learning.

One goal of our group is to provide research-based publications on current topics in CEA. For example, in 2019, our group collaborated on a literature review of food production in controlled environment agriculture in an urban setting (Gómez et al., 2019; CT, FL, IA, IN, NJ, NC, MI).

This manuscript reviews critical aspects of CEA production including the production environment, lighting, carbon dioxide enrichment, and specialty production systems such as hydroponics. It has already been cited 58 times since publication.

Various group members organize webinars or participated in webinar series focused on greenhouse and indoor vertical farm based controlled environment crop production. For instance, AZ organized ISHS VerticalFarming Talks webinar series with 13 presentations with speakers from around the world with topics including lighting, environmental control, co-optimization of environment variables, economics, life cycle assessment, advances in vertical farming, and reached more than 5000 viewers.

To improve the ease of collaboration, OH created a directory of contact information for Extension Specialists throughout the United States in 2022 to make it easier for CEA researchers, educators, and Extension personnel to connect. Faculty at land-grant universities in nearly every state are members of this group along with several USDA-ARS research scientists who work in CEA. This contact group is relatively new, but it has already served to share information about upcoming Extension programs and assistantships available for new MS or PhD students. OH is working with each member of this group to develop a list of greenhouses and vertical farms throughout the US.

Methods

Objective 1.

Environmental control and management (lighting, temperature, CO_2 enrichment, and nutrient)

We will perform a series of experiments to further understand the interactions between light properties and other environmental and cultural factors. We will focus on balancing energy input and growth and quality attributes of emerging and less studied hydroponic crops, including hot pepper, spinach, and arugula. We will grow plants under sole-source, color-tunable LED fixtures on vertical shelves in a growth room or in reach-in growth chambers with independent environmental control. Over time, we will test various combinations of the photon spectrum, intensity, and duration, aerial environmental factors, and nutrient solution factors. When plants are ready for harvest, we will measure plant shoot and root biomass, morphological traits, pigmentation, mineral nutrient concentrations, and photosynthetic parameters, as well as assess physiological disorders, if present.

We will comprehensively examine plant growth, nutritional quality, morphological and physiological responses to temperature and sole-source electric lighting conditions (spectral quality, intensity, and photoperiod) in growth chamber studies. Multiple leafy green crops will be selected based on their commercial value, suitability for indoor farming, and nutritional values. Results from those experiments will be used to develop integrated lighting and temperature control strategies for improved crop yield and quality, and ultimately to facilitate the development of energy-efficient management approaches for lighting and cooling.

We will conduct a series of studies to characterize the effects of CO_2 enrichment, nitrogen availability, and light conditions on plant growth, quality, transpiration, and water use efficiency; interactive effects among the environmental factors will be examined.

We will perform a series of greenhouse experiments to determine end-of-production lighting strategies to increase culinary herb volatile concentration and flavor while enhancing post-harvest longevity. We will grow plants in a greenhouse and subject plants to altered light intensity and/or quality for different durations at the end of production. We will quantify plant morphology, yield, photosynthesis, volatile concentrations, and consumer preference.

Climate control technologies and algorithms development

We will model the different techniques for dehumidification of various indoor vertical farming settings with various types of crops. Then, we will select some best potential solutions for optimization in indoor farming applications and test the prototype units in terms of their performance for moisture removal and energy consumption.

We will investigate the correlations between canopy microclimate, air distribution, and crop growth with computational fluid dynamics to achieve precision microclimate control for crop production in indoor farming to improve energy use efficiency.

We will use previously developed greenhouse and vertical farm energy models to compare energy use of tomatoes and strawberries in different U.S. climates.

We will conduct greenhouse experiments using a hydroponic system and lettuce as a model crop. A machine learning control algorithm will be integrated into an existing commercial control system. Crop production experiments will be conducted comparing yields and resource consumption for crops grown using either a conventional environmental control approach versus a control approach that incorporates sophisticated models and predictive techniques.

We will co-optimization of environmental variables, alternative air distribution system designs that can help enhancing resource use and reducing energy costs are needed.

We will conduct greenhouse experiments using drip irrigation-based system with tomato as model crop in a greenhouse located in semi-arid climate. Crop production experiments will be conducted comparing yields and resource consumption with water and energy using a conventional environmental control approach versus a control approach that incorporates predictive models and AI integrated controls.

We will conduct experiments to quantify the interactive effects of light, temperature, and CO_2 concentration on crop growth, morphology, yield, and photosynthetic rate. Focus crops will be culinary herbs, young plants (liners), and other specialty-crops. Photosynthetic response measurements will be made using a LI-6800 portable photosynthesis system and modeled.

We will conduct a series of greenhouse experiments to identify suitable species and cultivars for high yield, high resistance to abiotic (heat) and biotic (pests and diseases, bolting and tip burn, if applicable) stresses. We will select promising genotypes for further study to optimize the production protocol, including nutrient management, root zone temperature, and supplemental lighting strategies in winter season. Sensory relevant parameters such as color, chlorophyll content, texture, taste (non-volatiles), and aroma (volatiles) will be quantified. Flavor instrument analysis data will be correlated to consumer test data to discover the key flavor compounds associated with consumer sensory preference. In addition, nutrient compositions such as total polyphenols, individual polyphenols, vitamin C, and mineral profiles will be further used as quality indicators for the leafy greens in the study.

Objective 2.

We will conduct trials with a variety of crops that are not yet widely grown hydroponically using nutrient film technique (NFT) and in soilless substrates. The yield and the overall quality of the crops in both systems will be compared . Previous work has indicated that some crops, such as carrots, have lower visual quality when grown in NFT, however, some cultivars performed better than others (Gichuhi et al., 2009). Crops grown in both systems will be analyzed for texture, sweetness, and flavor through sensory evaluation.

For organic soilless cultivation and hydroponics, we will investigate the effectiveness of beneficial microorganisms and controlling rootzone environments for organic hydroponic crop production. Organic fertilizers require microbially mediated mineralization and nitrification processes, which can be affected by rootzone environment, such as pH, dissolved oxygen concentration, and temperature. Thus, when organic fertilizers are used, the effects of the hydroponic rootzone environment on plant nutrient uptake and growth as well as microbial activities and mineralization and nitrification process should also be considered. Optimization of the environmental and microbial components in the rootzone will improve the efficacy of using organic fertilizer in hydroponic systems.

A series of experiments will be conducted to determine the effectiveness of various plant biostimulants on the promotion of growth and quality of onion and watermelon seedlings and possibly other vegetable seedlings and the carry-over benefits after transplanting. In addition, experiments will be carried out to optimize organic fertility management using representative organic fertilizers for transplant production with or without the use of PBs.

We will determine how nutrient solution and air temperature interact to increase the yield, post-harvest longevity, flavor, and quality of culinary herbs. Plants will be grown at three air temperatures (20 to 40 °C) and five nutrient solution temperatures (15 to 40 °C) depending on the crop. A minimum of 10 plants per treatment per replication will be grown and growth, production time, plant appearance, and yield will be assessed. Photosynthesis (CO_2 assimilation) and key volatile compounds will be quantified for 4 plants per treatment per replication with an LI 6800 portable photosynthesis system and GC-MS, respectively.

The overall research goal for aquaponics is to develop and test aerobic digestion of solid fish waste as a value-added organic fertilizer that can also be divert large scale commercial fish waste solids from the waste stream. Research will be completed by 1) constructing 4 aerobic digesters, 2) testing the digesters as an organic nutrient source in hydroponics with leafy greens and herbs,

3) using the aerobic digestate as a fertilizer source for organic vegetable transplants, and 4) estimating nutrient elements N and P.

Objective 3.

All team members have committed to involve undergraduate students in independent research related to this project. We strongly believe that the future of our industry depends on well-trained individuals.

We will continue to train graduate students and involve them in this project. We regularly invite graduate students to attend our meeting and present their work. In the past, we have financially incentivized student attendance through a poster and oral competition and providing travel grants.

We will continue to host short courses on hydroponics, energy efficiency, water management, and general controlled environment production practices. Our members with Extension appointments will continue to organize annual greenhouse workshops and short courses in AZ, CT, IA, KS, NJ, NY, OH, TX. During these short courses, we will provide opportunities for graduate students to present about their research and activities to the participants, as part of the facility and technical tour programs. In all of these instances, we will invite members from other stations to participate as speakers. Upcoming events include the Northeast Greenhouse Conference (November 2023 and 2025), the 4th Annual Controlled Environment Conference at Dallas AgriLife Research and Extension Center (December 6-7, 2022), Great Plains Growers' Conference (January 13-14, 2023), 22nd Annual UArizona Greenhouse Engineering and Crop Production Short Course (March 15-17, 2023), and NCERA 101 at UC Davis in April 19-21, 2023. Many of the events we host for members of the industry are offered every year or every other year and our programming focuses on providing the most current information.

Many of our members have outfitted greenhouse sections with diverse production systems (horizontal and vertical hydroponic growing systems, as well as traditional pot-and-media based systems) that students use to learn about different growing techniques, sensors and instrumentation, environmental controls. We all have agreed to continue to do hands-on training sessions in CEA-related courses to increase practical training.

We will work as a group to develop a curriculum for undergraduate courses in hydroponics to increase the ease of offering courses in this important area. These courses include a new course for engineering students at UC Davis addressing the control and optimization of microclimates, equipment (HVAC, irrigation, control systems) and materials (cover, screen, etc.) selections, and using simulation software for energy calculations. The University of Maine is working with Cornell University and the University of Vermont to develop an online greenhouse scouting course. This course will focus on instruction about the tools and techniques involved in scouting greenhouses for insect, mite, or disease problems. Scouting is a cornerstone of integrated pest management and allows growers to be offered to greenhouse growers and undergraduate students. Participants can receive a certificate in scouting, which would support training of future professional scouts.

Much of our education and outreach efforts will focus on providing instruction to growers and undergraduate students in the area of hydroponics. This has become an important area for education, because hydroponics allows for the production of food crops year-round in a variety of climates with less water and fertilizer. Hydroponic food production in the US has increased rapidly, and our educational efforts will ensure that current and new growers are using best practices.

Other member stations, including Cornell University, Iowa State University, Texas A&M University, Kansas State University, University of Arizona offer undergraduate and graduate level courses in Hydroponics and Soilless Crop Production. The courses focus on the science, management practices, and engineering in controlled environment crop production using hydroponics and will enable students to set up hydroponic systems and cultivate diverse crops such as leafy greens, microgreens, fruiting vegetables and small fruits in a research and commercial production setting. Curriculum development and in-class experiences at KS and TX will help to guide development of additional new hydroponics courses at other member stations developing their CEA curriculum.

We plan to write a hydroponics textbook for undergraduate students and CEA industry members that will support the development of new hydroponics courses or Extension training. The writing and editing of this book will be led by IA, MI, NJ, and NY and will be based on an outline for the book that our group wrote in 2021. Other members will contribute chapters to the book based on their diverse expertise.

Measurements of Progress and Results (Outputs)

Objective 1.

- Develop lighting strategies based on environmental and cultural conditions for efficient indoor production of emerging crops.
- Develop integrated lighting and temperature control strategies for improved crop yield and quality, and to facilitate the development of energy-efficient management approaches for lighting and cooling.
- Develop efficient thermal environment management guidelines to reduce the carbon footprint of indoor farms, improve crop water use efficiency, and reduce energy consumption.
- Add models fit to the data for PhotoSim, which will allow growers to evaluate how altering the growing environment will affect photosynthetic rates, yield, and compare costs for various environmental set points.
- Develop an efficient dehumidification system in terms of energy use and humidity control.
- Model energy use and carbon emissions of tomatoes and strawberries in greenhouse and vertical farms.
- Develop microclimate control algorithms to promote crop quality and energy use efficiency.
- Determine the genotypes of leafy greens with high yield, high-stress tolerance for year-round production.

- Identify cost-effective strategies such as end-of-production (EOP) regimens to improve the yield, appearance, nutritional content, and post-harvest longevity of leafy greens species and cultivars.
- Develop guidelines for cost-effective end-of-production lighting strategies to enhance crop flavor, aroma, and appearance.
- The controlled environment industry will be educated about the use of advanced control tools that improve plant quality and reduce resource consumption.
- Develop machine learning powered control algorithms for greenhouse environmental control.
- Evaluate alternative air distribution system design configurations that can be suited to variety of vertical farming production system designs.

<u>Objective 2.</u>

- We will select at least two new crops for hydroponic production based on yield, quality, and flavor (ME).
- We will develop cultural practice guidelines for using organic fertilizers in hydroponic systems for common hydroponic crops, including leafy vegetables, herbs, and strawberries (AZ, KS, TX).
- We will evaluate the effectiveness of selected plant biostimulants (PB) on mitigating drought stress using onion and watermelon as model crops. The optimal application methods and rates of the top performing PBs will be determined. The best organic fertilizers and their application methods and rates will be determined. In addition, the synergistic or interaction of organic fertilizers and PBs will be investigated (TX, UT).
- We will develop integrated air and root-zone temperature management guidelines for five culinary herb species that maximize growth, shelf-life, and flavor (TN, TX).
- The resulting product from the aquaponics research is a high-value fertilizer which diverts fish waste from waste-streams (NY).

<u>Objective 3.</u>

- We will organize education programs that target CEA growers around the US, our target populations will include Hispanics, Native Americans, and new farmers.
- We will publish an online hydroponics production book.
- We will enhance undergraduate and graduate research training on controlled environment plant production to prepare the students for careers in the field.
- We will develop and share curricula related to hydroponic food production in CEA, including controlled environment engineering applications.
- We will publish scholarship of teaching and learning that demonstrates and enhances effectiveness of our programming efforts.

Outcomes or Projected Impacts

In response to the outputs of this project, we anticipate that:

<u>Objective 1.</u>

- We will improve crop growth and nutritional value while saving electricity and carbon emissions by optimizing growing environments based on key environmental and cultural factors.
- We will improve crop production, reduce water use, and reduce energy consumption for dehumidification.
- We will improve crop models to help improve grower's decision-making, focusing on culinary herbs, young plants (liners), and other specialty-crops.
- We will improve the sustainable production of crops in CEA systems through HVAC system design.
- We will inform the research community about the benefits of implementing advanced control approaches/algorithms.

Objective 2.

- More crops suited for greenhouses and indoor farms will be available for producers with production protocols (ME).
- The effectiveness of selected commercial plant biostimulants (PB) on promoting the growth and quality of onion and watermelon seedlings under stressed and non-stressed conditions will be determined. The optimal application methods and rates of the top performing PBs will be identified. The best organic fertilizers and their application methods and rates will be determined. In addition, the synergistic effect of organic fertilizers and PBs will be investigated. These results will guide organic producers in selection of organic fertilizers and PBs (TX, UT).
- Nearly 90% of NYS's population lives in urban areas and aquaculture, aquaponics, and hydroponics are common urban agriculture practices aa land-efficient systems producing high nutrient density fish and vegetables. These systems are also often used in school science and agriculture programs. Fish farming produces large volumes of solid-waste, and this project will develop low-cost aerobic digestion methods to that can reduce solid waste (and N and P) by more than two-thirds for NY's 105 aquaculture farms. We will develop and test a low-cost fertilizer source which can be utilized by hydroponic and certified organic vegetable transplant growers. Continual interaction with NY stakeholders will ensure the project is rooted in real-world production methods and crops. Dissemination will take place via on-site tours, an annual aquaponics short course, a workshop for educators, and the project website at cea.cals.cornell.edu ensuring that diverse stakeholders can benefit from project findings (NY).

Objective 3.

- The proposed book on hydroponics will help keep growers competitive and aware of the latest research in controlled environment agriculture.
- New courses focusing on hydroponics and agricultural engineering will train the next generation of growers.

Milestones

Annual recurring milestones

AK, AZ, CA, DE, FL, MI, NJ, NY, TN, TX, and USDA-ARS will collaborate to optimize environmental management and control to reduce energy use for high-quality greenhouse and indoor crop production through environmental control and management, climate control technologies and algorithms development, and optimizing crop growth with crop modeling and selection.

Teach undergraduate and graduate courses on controlled environment crop production practices and agriculture engineering: CA, DE, IA, KS, ME, FL, NJ, TX, AZ.

Communicate new horticultural knowledge with local, regional, and national stakeholders: KS, MN, OH, NJ, NY, TX, AZ.

2023 to 2024.

Objective 1.

- Set up new lab spaces and hardware for indoor crop experiments in DE.
- Set up a multi-chamber canopy gas exchange system equipped with LEDs lights and capable of temperature control; re-model lab space for indoor crop cultivation/research in TX.
- Set up and test the new indoor growth facility in USDA-ARS.
- Work for more precise tools for dehumidification demand and simulate the performance of the possible solutions under various settings in CA.
- Set up a growth chamber equipped with an engineered air distribution system in FL
- Screening 20 leafy greens and determining their suitability for warm climate greenhouse hydroponic production in TX.
- Plan and prepare for end-of-production lighting experiments in TN.
- Completed growing system installation and control hardware setup and testing for greenhouse experiments in NJ.
- Determine the impact of CO_2 enrichment with real-time lighting control for hydroponic greenhouse lettuce in NY.
- Model energy use and carbon emissions of tomatoes in greenhouse and vertical farms (NY).
- Design and construct air distribution system in the vertical farm facility for experiments in AZ.
- Completed growing system, sensors and instrumentation installation, control hardware setup and testing for a control approach greenhouse climate control in AZ.

Objective 2.

- Two to three crops will be grown in NFT (ME).
- Conduct research determining which microbial inoculants are beneficial in organic hydroponic production in leafy vegetables and herbs (AZ, TX).

- Identify the most effective plant biostimulants; screening organic fertilizers for seedling propagation (TX).
- Plan and prepare for root-zone temperature experiments (TN, TX).
- Construct 4 aerobic digesters (NY).

Objective 3.

- Members of the group will edit our existing outline for a book on hydroponics as needed.
- Member stations that instruct courses in hydroponics will work together to share curriculum plans.
- A new online course on greenhouse scouting will be offered to greenhouse growers and undergraduate students in spring, 2023 and fall, 2024.
- Continue offering intensive workshops and short courses to educate public and practitioners of CEA.

<u>2024 to 2025.</u>

Objective 1.

- Conduct experiments on light and environment interactions in hot pepper in DE.
- Examine the interactive effects of light spectral quality by temperature in vegetable crops in TX.
- Conduct lighting and temperature experiments in culinary herbs in USDA-ARS.
- Design prototype units as a sustainable solution for dehumidification and testing in small-scale CEA facilities in CA.
- Investigate the correlation between air distribution and canopy microclimate in FL
- Screening 20 leafy greens and determining their suitability for warm climate greenhouse hydroponic production in TX.
- Conduct end-of-production lighting greenhouse experiments in TN.
- Completed baseline experiments in NJ.
- Determine the impact of CO_2 enrichment with real-time lighting control for hydroponic greenhouse tomatoes in NY.
- Model energy use and carbon emissions of strawberries in greenhouse and vertical farms (NY).
- Conduct experiments to evaluate crop growth, tipburn mitigation, environmental uniformity in indoor farming in AZ.
- Completed experiments with data collection on crop yield, greenhouse environment, and resource use in AZ.

Objective 2.

- Two to three crops will be grown in NFT (ME).
- Conduct research determining which microbial inoculants are beneficial in organic hydroponic production in strawberries (AZ, TX).
- Identify the most effective plant biostimulants and their applicate rates (TX).

- Conduct root-zone temperature experiments (TN, TX).
- Test the digestates as an organic nutrient source in deep-water culture hydroponic systems with leafy greens and herbs (NY).

Objective 3.

- Chapters will be assigned to members of the group who will contribute to the book on hydroponics.
- At least two member stations will offer courses in hydroponics; their experiences will inform the development of the book on hydroponics.
- Continue offering intensive workshops and short courses to educate public and practitioners of CEA.

<u>2025 to 2026.</u>

Objective 1.

- Conduct experiments on light and cultural factor interactions in hot pepper in DE.
- Examine the interactive effects of light spectral quality by temperature in ornamental transplants in TX.
- Conduct lighting and CO2 experiments in culinary herbs in USDA-ARS.
- Design prototype units as a sustainable solution for dehumidification and testing in small-scale CEA facilities in CA.
- Evaluate the techno-economic feasibility of indoor production with some feasible solutions in CA.
- Conduct experiments to study plant growth under different air distribution treatments in FL.
- Determine the root zone temperatures for cooling and consumer preference of selected promising leafy greens in TX.
- Conduct end-of-production lighting greenhouse experiments in TN.
- Informed/trained growers about improved control strategies, completed experiments in NJ.
- Determine the impact of CO_2 enrichment with real-time lighting control for hydroponic greenhouse tomatoes in NY.
- Model the energy use and carbon emissions benefits of artificial intelligence in climate control of greenhouse and vertical farm production (NY).
- Conduct experiments to evaluate co-optimization of environmental variables with DLI, air temp, CO_2 and VPD in AZ.
- Completed experiments with data collection on crop yield, greenhouse environment, and resource use in AZ.

Objective 2.

- At least one additional crop will be grown in NFT; crops will be evaluated using sensory analysis (ME).

- Conduct research determining the impacts of controlling rootzone environment in organic hydroponic production in leafy vegetables and herbs (TN, TX).
- Identify the most effective plant biostimulants and their applicate rates; determine the interaction and/or synergistic effects of organic fertilizers and PBs (AZ, TX).
- Conduct root-zone temperature experiments (TN, TX).
- Evaluate aerobic digestates as fertilizer source for organic vegetable transplants (NY).

Objective 3.

- Members will write and edit chapters for the book on hydroponics.
- Continue offering intensive workshops and short courses to educate public and practitioners of CEA.

2026 to 2027.

Objective 1.

- Conduct experiments on light and environment interactions in leafy greens in DE.
- Characterize the effects of CO_2 enrichment and light conditions on plant growth, quality, transpiration, and water use efficiency in TX.
- Conduct environmental experiments on young plants in USDA-ARS.
- Improve and increase the sustainability of indoor productions in CA.
- Conduct experiments to study plant growth under different air distribution treatments in FL.
- Determine the root zone temperatures for cooling and consumer preference of selected promising leafy greens in TX.
- Complete volatile compound quantification in TN.
- Informed/trained growers about improved control strategies, completed experiments in NJ.
- Model the potential for green energy and geothermal systems for greenhouses.
- Comparisons for effectiveness of air distribution system designs in AZ.

Objective 2.

- Conduct research determining which microbial inoculants are beneficial in organic hydroponic production in strawberries (AZ).
- Determine the interaction and/or synergistic effects of organic fertilizers and PBs (TX)
- Complete volatile compound quantification (TN).
- Estimate the N and P quantity diverted from waste streams (NY).

Objective 3.

- Community outreach about advance control strategies with AI integration in AZ.
- Members will continue to write and edit chapters for the book on hydroponics.

- Continue offering intensive workshops and short courses to educate public and practitioners of CEA.

2027 to 2028.

Objective 1.

- Conduct experiments on light and cultural factor interactions in leafy greens in DE.
- Characterize the effects of light conditions, CO2, and nutrient availability on plant growth and quality in TX.
- Conduct environmental experiments on other specialty crops in USDA-ARS
- Adapting the proposed solutions for commercial scale production as energy efficient and sustainable approaches for dehumidifying indoor farming systems in CA.
- Develop intelligent environmental control algorithms for indoor farming in FL.
- Determine the nutritional quality parameters for the selected promising leafy greens in TX.
- Provide recommendations for end-of-production lighting in culinary herbs in TN.
- Informed/trained growers about improved control strategies, completed final experiments, published results and developing a plan for the next steps in NJ.
- Model the potential for green energy and geothermal systems for vertical farms.
- Prepare recommendations for air distribution system alternatives and environmental control strategies in AZ.
- Completed experiments, published results, and community outreach with presentations at conferences, workshops, webinars in AZ.

Objective 2.

- Develop the cultural practice guidelines of using organic fertilizers in hydroponic systems for common hydroponic crops, including leafy vegetables, herbs, and strawberries (ME, AZ, TX, TN, NY).
- Determine the optimal PB rates and organic fertilizer rates (AZ, TX).
- Provide recommendations for culinary herb air and root-zone temperature (TN).
- Extension activities on aquaponics will be followed (NY).

Objective 3.

- Our book on hydroponics will be published.
- Continue offering intensive workshops and short courses to educate public and practitioners of CEA.

Outreach Plan

We will work closely with the controlled environment agricultural industry throughout the United States. Several team members have Extension appointments, providing additional connections with grower associations, industry suppliers, and the Land-grant Extension network.

We use these connections with the industry to answer questions that are based on actual industry needs and to communicate the new knowledge that we generate.

We plan to continue sharing the results of our research through a variety of methods to reach both our peers at research institutions, as well as greenhouse growers, industry suppliers, and Extension personnel. Results will be published in refereed journal articles and Extension publications.

A large number of our members, in collaboration with industry participation, organize annual education programs for greenhouse growers. In these venues, we will collaborate with our peers and cross state borders to share our knowledge.

We plan to publish a book on hydroponic production for greenhouse growers that will include the results of our group's previous work on water and energy savings, ventilation and cooling, and alternative energy use.

We will work closely with the Northeast Greenhouse Growers Association and the Michigan Growers Association annual meetings which have an attendance of over 800. We will also write articles for trade magazines with readerships of >18K (Greenhouse Grower, GrowerTalks and GPN Magazine) and repost in HortiDaily and VerticalFarming Daily which has a readership of > 20K world-wide.

Over the years, members of this project have provided valuable greenhouse engineering technology to the industry throughout our history through technology transfer. Some examples include the use of air–inflated double–layer polyethylene films as greenhouses cover material, advances in hydroponic production systems and supplemental lighting, floor heating for greenhouses, the use of energy curtains, air distribution system design, environmental controls. Many of the technologies originally developed by members of this project are now industry standards for improving sustainability and/or conserving energy. Several key industry members received part of their education at the institutions (and in some cases were instructed by members of our team) involved in this project.

We are distinctively qualified to develop strategies that address resource management in controlled environment agriculture. Our group consists of plant scientists, agricultural engineers, and an agricultural economist. Our group includes early-, mid-, and late-career researchers. The extent of diversity in terms of area of expertise, career stage, demographics, and location provide a valuable contribution to the industry in which practical and research-based solutions are quickly developed and spread in time and space.

Organization/Governance

The technical committee has organized itself by annually appointing an incoming secretary, who then serves as the secretary for the following year (including the next annual meeting). The secretary will complete a one-year term and then serve as the committee chair the following year. We do not have the position of vice chair (chair elect). Therefore, officers served for two-year terms. This limited the time commitment requested from incoming officers and since the committee was small and informal, sufficient institutional memory could be tapped in case procedural questions came up. Annual meetings were organized on a rotating basis after the membership was polled for availability and interest. This organizational model has worked well for many years, and we plan to continue with it if our proposal is approved for continued funding. Many of the participating members meet each other at other scientific meetings throughout the year, ensuring sufficient opportunity for interaction in addition to the annual project meetings.

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