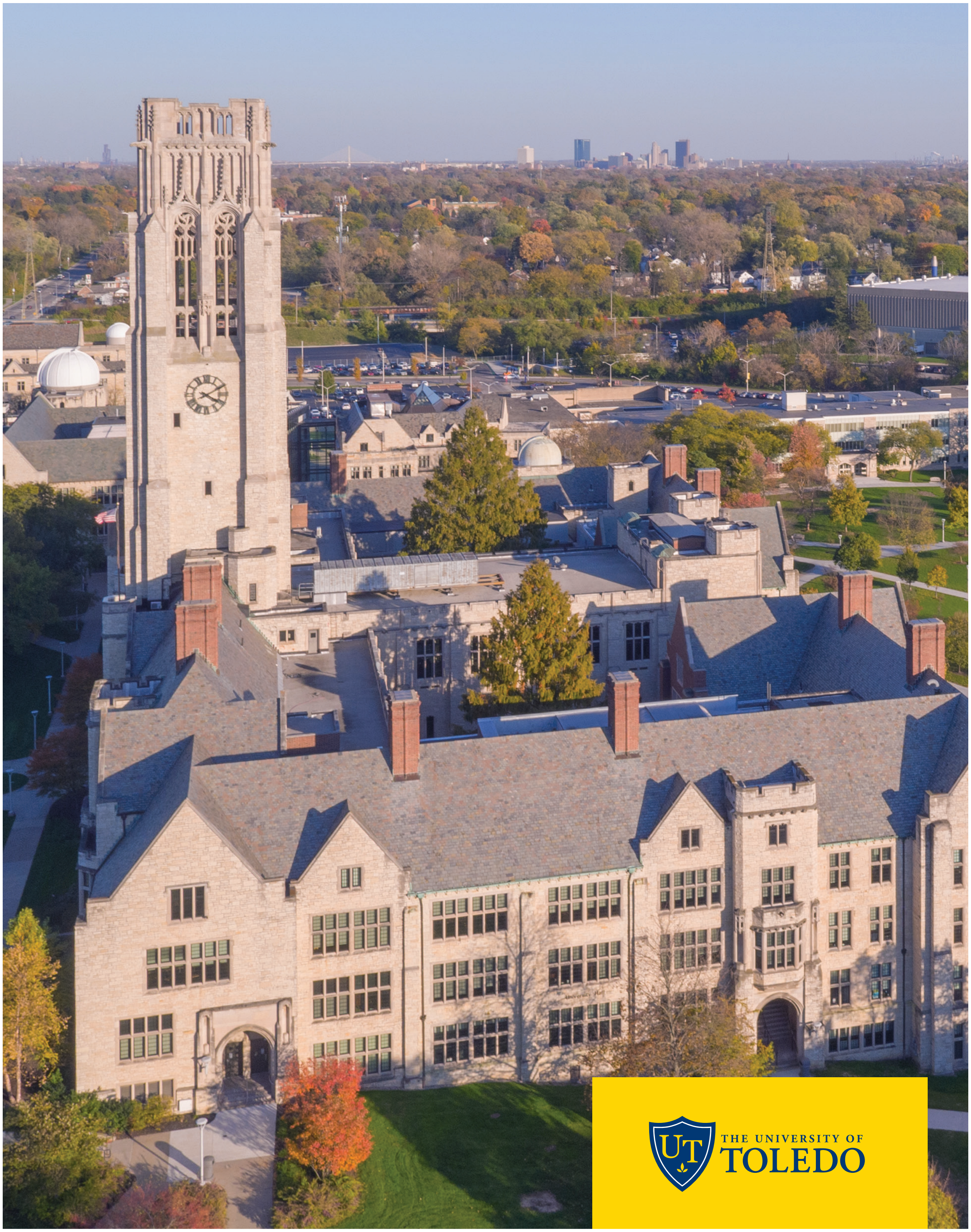
Multi-agency Collaboration Addressing Challenges in Controlled Environment Agriculture



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Multi-Agency Collaboration Addressing Challenges in Controlled Environment Agriculture: WORKSHOP REPORT

James Altland, Defne Apul, Kale Harbick, Kai Ling, Glenn Lipscomb, and Jennifer Stokes-Draut

I. Executive Summary

This report summarizes a virtual workshop on collaborative Controlled Environment Agriculture (CEA) research held November 2-5, 2021, and cohosted by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS), Lawrence Berkeley National Laboratory, representing research by the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and The University of Toledo (UToledo). The workshop engaged stakeholders, experts, and researchers from across the hosting organizations and beyond in interdisciplinary discussions on the potential for CEA to become a more significant contributor to U.S. food systems. Participants collaborated to identify major themes for research and development (R&D) challenges, opportunities, and needs as well as associated research questions.

Introductory remarks were delivered by:

- Rep. Marcy Kaptur (OH-09)
- Rep. Barbara Lee (CA-13)
- Frank Calzonetti, Vice President of Research, The University of Toledo
- Steven Kappes, Associate Administrator, USDA-ARS
- Mike Witherell, Director, Lawrence Berkeley National Laboratory
- Kale Harbick, Research Agricultural Engineer, USDA-ARS
- Ray Wheeler, Plant Physiologist, NASA

Controlled environment agriculture is an important component of our diverse food system. It encompasses a broad spectrum of facilities and technologies, ranging from simple high tunnel or hoop-house structures with little or no environmental control technology to modern greenhouses with computer-controlled heating, cooling, and supplemental lighting to completely indoor plant factories that grow plants on stacked shelves in warehouse-like structures using 100% artificial lighting and computer-controlled environmental systems.

Although CEA production can be an energy- and resource-intensive process, it also shows promise as a way of improving food access, food security, nutrition, and health, while using energy, water, and other resources more efficiently. Production system design involves trade-offs between energy efficiency and space efficiency. In climates in the contiguous U.S., properly designed and controlled greenhouses generally use less energy for equivalent production compared to plant factories. Greenhouses require more energy for heating, especially in northern latitudes, but use much less energy for cooling, dehumidification, and lighting than plant factories, which exclusively utilize electric lighting; however, plant factories can be much more space efficient than greenhouses if they have multiple stacked layers for plant production. Both urban plant factories and peri-urban greenhouses can drastically reduce transportation energy, carbon footprint, costs, and food waste due to a shorter distance and time from harvest to market.

The objective of this workshop was to identify critical needs and research questions that would improve the productivity, efficiency, and social and environmental sustainability of CEA production systems. A secondary goal was to facilitate a dialogue between ARS, DOE, NASA, UToledo, and other participating industry and academic leaders on how the aforementioned agencies and participants can collaborate and leverage existing resources and expertise to address the identified research questions.

This report contains a synopsis of the technical talks presented related to 1) plant science; 2) energy technologies; and 3) social and systems analysis. These summaries are followed by synopses of the challenges, needs, and opportunities (CNOs), and research questions (RQs) identified for each theme. The report concludes with selected visionary responses given by workshop participants when asked to respond to the question: "What do you think controlled environment agriculture could look like in five years if collaborative research between ARS, DOE, NASA, and others is successful?"

This report is the deliverable from the workshop and will be shared with Congress, participating agencies, and other participants that can be used as a guide to shape research objectives over the next 10 years.

Significant Findings

- There has been a rapid expansion of CEA, especially greenhouse hydroponic vegetable production, around the world and in the U.S. Over 90% of greenhouse vegetable production is tomatoes, followed in small fractions (1% to 4%) by cucumbers, peppers, eggplants, and lettuce.
- CEA production can be an energy- and resource-intensive process, it also shows promise as a way of improving food access, food security, nutrition, and health, while using energy, water, and other resources more efficiently.
- Due to the contained and controlled nature of CEA operations, it is important to develop ways to control seedborne pathogens and mechanically transmitted diseases in operations.
- The economic viability of CEA depends strongly on optimizing water use to reduce operating costs. The prevalence of hydroponic production systems calls for ways to operate CEA with zero wastewater discharge.
- Sensors and control algorithms are essential in many CEA operations, especially as they relate to reducing energy and resource inputs and this calls for the need for the next generation of sensors and data integration in operations. Multi-spectral and hyper-spectral imaging systems are becoming more affordable and provide new options in early disease detection and assessing water stress.
- Plant genetics and breeding efforts can identify and develop cultivars optimized specifically for CEA operations.
- It is important to improve the resource use efficiency of a crop growing under various CEA conditions to maximize the yield (biomass production) and improve the crop quality (flavor, taste, and phytonutrients).
- Membranes can be used in CEA to cool and dehumidify air, thereby reducing loads on heating, ventilation, and air conditioning (HVAC) systems, saving energy, and recovering water.
- Climate change may affect decisions about CEA locations as crop yields will increase in some regions but decrease in others.
- Co-locating a CEA production facility near a CHP plant is a common practice in Europe and has great potential in the U.S. as well. It has significant potential to reduce the carbon footprint and energy consumption of CEA.
- Technoeconomic analysis (TEA) and life cycle assessment (LCA) should be used to evaluate the tradeoffs for different design scenarios
- Social sustainability impacts (e.g., justice, food safety, nutrition, labor, workforce training) should be addressed up front in the development of CEA systems. Well-planned CEA may be able to create a restorative food system that improves public health, alleviates disparities, offers low investment alternatives, and improves environmental justice.

Workshop Process

A series of technical presentations were grouped into three one-hour sessions. The sessions were devoted to 1) plant science, 2) energy technologies, and 3) social and systems analysis. After each session, workshop participants were asked to identify research CNOs based on the presentations. Participant input was captured online using the proprietary XLeap platform. Participants also were asked to identify RQs based on the CNOs. Workshop organizers consolidated the lists of CNOs and RQs generated from the preliminary polling of the participants and grouped the responses into nine research themes: 1) microbiome, 2) pests, disease, and beneficials, 3) energy efficiency, 4) water and waste management, 5) sensors and testbeds, 6) environmental sustainability impacts, 7) social sustainability impacts, 8) genetics, and 9) systems integration and resilience. Participants then ranked the importance of each CNO and RQ on a five-point Likert scale, with 5 indicating the highest level of importance. Research questions identified as high priority will serve as initial catalysts for collaborative projects between the aforementioned agencies and participants.

Discussion Highlights

Discussion occurred in an online meeting. Input was obtained directly from invited stakeholders, representatives from the three federal agencies, and academic participants as well as the RQs and CNOs. The Likert scale gradings were obtained via Xleap. In the **microbiome** theme, discussion focused on how the microbiome can be controlled to maximize crop productivity and improve sustainability in CEA systems. Due to the contained and controlled nature of CEA operations, most discussion in the **pests, diseases, and beneficials** theme revolved around how seedborne pathogens and mechanically transmitted disease could be controlled. The **energy efficiency** theme emphasized how energy consumption could be reduced in energy-intensive activities. The prevalence of hydroponic production systems directed discussions in **water and waste management** toward the feasibility of operating CEA with zero wastewater discharge. Sensors and control algorithms are essential in many CEA operations, especially as they relate to reducing energy and resource inputs. In discussions of **sensors and testbeds**, the conversation centered on the need for the next generation of sensors and data integration in CEA. In the **genetics** theme, there were discussions on how plant genetics and breeding efforts can identify and develop cultivars optimized specifically for CEA operations. Apart from the technical aspects of CEA production, there was robust discussion on how CEA can be utilized to improve environmental and economic sustainability in U.S. agriculture and society in the **environmental sustainability and social sustainability themes**. Finally, there were conversations on strategies for designing for **system integration and resilience** of CEA in the face of climate change and other social and economic drivers.

THEME	OVERARCHING RESEARCH QUESTION	RESEARCH PROGRAM
Microbiomes	How can CEA microbiomes be controlled to maximize productivity and improve sustainability?	Tools for characterizing and manipulating CEA microbiomes are sought. Specific areas of research include: 1. What are the molecular mechanisms by which the microbiome influences crop health, productivity, and nutrient consumption? 2. How can the microbiome be controlled or amended to promote nutritional value and improve sustainability? 3. How can microbiomes be characterized and monitored?
Pests, diseases, and beneficials	How can seedborne pathogens and mechanically transmitted disease be controlled in CEA?	Disease and pest control options in CEA are limited and novel techniques are needed to reduce the potential for catastrophic crop losses. Specific research topics include: 1. How can speed breeding and biotechnology, especially gene-editing technologies, be used to develop intrinsically healthier CEA cultivars? 2. What seed treatment procedures are most effective against seedborne pathogens? 3. Can novel biological control agents and chemotherapy measures be developed for pest and disease control in CEA? 4. How can open plant pathology methods be implemented across the CEA industry to promote plant health?
Energy efficiency	How can CEA energy consumption be reduced?	Technologies for monitoring and reducing CEA energy consumption are sought. Specific areas of research include: 1. What technologies can enhance CEA building envelope thermal and optical properties? 2. How can natural light be supplemented with artificial light to optimize CEA productivity? Is light needed? 3. How can CEA thermal loads be handled with innovative HVAC systems or integrated with other infrastructure?
Water and waste management	Can CEA be operated with zero wastewater discharge?	What operational and technological innovations can lead to zero wastewater discharge (i.e., the only water that leaves the facility is the water embedded in the food produced)? Specific areas of research include: 1. How can water (and dissolved matter) be recycled within the CEA facility? 2. How can alternative water sources be utilized? 3. How can water flows within the CEA facility be reduced? 4. What is the impact of biofilm formation (beneficial and detrimental) in CEA?
Sensors and testbeds	What are the needs for the next generation of sensors and data integration in CEA operation?	What sensor innovations are needed to improve CEA productivity and sustainability? How can the data collected be used? Specific areas of research include: 1. What technologies can be used to improve sensor performance and utilization? 2. What new sensors are needed to complement current commercial units? 3. How can sensor data be better utilized to enhance CEA through machine learning or operational control?

THEME	OVERARCHING RESEARCH QUESTION	RESEARCH PROGRAM
Environmental sustainability	**In what ways does CEA improve environmental and economic sustainability?**	How can we design and operate CEA facilities so that they are more economically and environmentally sustainable than conventional systems? Specific areas of research include: 1. What baseline metrics [e.g., plant productivity, energy efficiency (% improvement), water efficiency, cost/acre] need to be met to make CEA competitive? 2. What are the effects of geographical location, size, and the technology on integration? 3. How should externalities be considered? 4. What Life Cycle Assessment (LCA) and Techno-economic Analysis (TEA) tools are needed to evaluate the above questions?
Social sustainability	**In what ways does CEA improve social sustainability?**	How can CEA be designed and operated to improve social impacts such as justice, food safety, nutrition, labor, and workforce training? Specific areas of research include: 1. How should social impact such as justice, food safety, nutrition, labor, and workforce training be assessed? 2. Who should be included in the CEA process? Who benefits from CEA production? Who is helped, displaced, or hindered by CEA? 3. How can CEA address the needs of low financial and skills resources communities?
Genetics	**How can plant genetics and breeding efforts be applied to crops grown in CEA?**	What are the genetic potentials under controlled environments for crop yield, quality, flavor, nutritional content, and plant architecture? Specific areas of research include: 1. How can USDA plant germplasm resources be used to identify and develop new plant materials suitable for CEA production systems (greenhouse and indoor vertical)? 2. Are new laboratory facilities needed for gene-editing and modifications to develop new cultivars useful for CEA productions? 3. How can rapid plant breeding be used to develop new cultivars and rootstocks that are suitable for CEA production (high yield, good quality, early maturation, and continuing production)?
System integration and resilience	**What are preferred strategies for system integration and design for resilience?**	In what ways does CEA increase or decrease the resiliency of our food supply system? What are the best technology integration strategies (which technology, how, for which context) for designing efficient, resilient, and sustainable CEAs? Specific areas of research include: 1. Can models be developed to estimate supply chain resiliency while accounting for predicted scarcity of resources and climate change adaptation needs? 2. Can the design process be improved to address tradeoffs for integrating different technologies into existing infrastructure systems to minimize impact on energy systems, transportation, food supply, building use, water demands, waste management, etc. and avoid unintended consequences?

II. Technical Presentation Synopses

Session 1. Plant Science, moderated by Dr. Kai-Shu Ling, USDA-ARS

Dr. Michael Bledsoe, Vice President on Food Safety and Regulatory Affairs, Village Farms
Controlled Environmental Agriculture (CEA): Greenhouse Hydroponic Vegetable Production

Recently, there has been a rapid expansion of CEA, especially greenhouse hydroponic vegetable production, around the world and in the U.S. Over 90% of greenhouse vegetable production is tomatoes, followed in small fractions (1% to 4%) by cucumbers, peppers, eggplants, and lettuce. In the U.S., 75% of retail fresh market tomatoes are from greenhouses. In North America, Mexico has 10,000 acres of greenhouses, followed by Canada with 4,000 acres, and the U.S. with 2,300 acres. Major challenges facing the U.S. greenhouse industry include high energy costs of electricity, natural gas, and petroleum; labor shortages; supply of seeds, water, and fertilizers; as well as food packing and distribution. Research needs include robotics, light emitting diode (LED) lighting, laser knives (for trimming leaves, stems, and fruits with less risk of pathogen or viral cross-contamination from plant to plant), disinfectants for crop application, and high disease resistance in scions and rootstocks (upper and lower portions of a grafted plant, respectively) against emerging diseases.

Dr. Kai-Shu Ling, Research Plant Pathologist, USDA-ARS, Charleston, SC
Overview of USDA-ARS Grand Challenge Synergy-Controlled Environment Agriculture

A brief overview was presented about the ARS Grand Challenge Synergy project focused on CEA. This Grand Challenge project was established in 2018, with over 30 ARS scientists with different expertise from 15 ARS locations across the U.S. Supervised and coordinated by ARS National Program Leaders, the project uses tomatoes as a case study and is organized into five objectives: 1) plant genetic and breeding; 2) energy and LED lighting; 3) water supply and substrates; 4) pest, disease, and pollinator health; and 5) food quality, safety, and human nutrition. A stakeholder advisory board was also established to guide research approaches and objectives. Research collaborations have been extended to other USDA agencies [Office of the Chief Scientist (OCS), Animal and Plant Health Inspection Service (APHIS), and National Institute of Food and Agriculture (NIFA)], other federal departments (DOE, NASA), and universities (The University of Toledo, University of Arizona, The Ohio State University, etc.).

Dr. Jennifer Boldt, Research Horticulturist, USDA-ARS, Toledo, OH
Plant Response and Yield in Controlled Environment Agriculture

Crop yield potential of a specific plant cultivar growing in CEA depends on various environmental factors, including light energy (light intensity and quality), temperature, carbon dioxide (CO_2), water, and fertilizer. For greenhouse production, available natural sunlight is affected by seasonal changes and geographic location; thus, supplemental light may be necessary to maximize yield potential. For indoor vertical farming, artificial lighting is needed for plant growth and crop production. It is important to improve the resource use efficiency of a crop growing under various CEA conditions to maximize the yield (biomass production) and improve the crop quality (flavor, taste, and phytonutrients).

Dr. Kateryna Zhainina, Postdoctoral Researcher, DOE Lawrence Berkeley National Laboratory
EcoPOD: Bridging the Gaps between Lab and Field

Plant-microbe-environment interactions are critical to earth systems processes; however, studying crops under field conditions is complex and can benefit from using fabricated ecosystem units. EcoPOD, with a fully automated environmental control system, can help bridge gaps between the lab and field when studying the mechanisms of interactions among plants, microbes, and environmental conditions.

Dr. John R. Stommel, Research Leader and Research Plant Geneticist, USDA-ARS, Beltsville, MD
Breeding for Adaptation to Controlled Environment Agriculture

Breeding for greenhouse production is well-established in the private sector, with elite crop cultivars and innovative crop management. In contrast, breeding for indoor vertical farming is still quite limited and faces profitability concerns. CEA offers some opportunities to overcome such challenges (e.g., using speed breeding under controlled environments to reduce the generation time and be able to evaluate more generations in a year). Other questions that need to be studied include: Can we enhance plant photosynthetic efficiency and production per unit of energy input? How can we develop new cultivars with enhanced resistance to emerging pests and diseases, and improve fruit quality and nutrition?

Dr. Anna Testen, Research Plant Pathologist, USDA-ARS, Wooster, OH
Plant Pathology and Disease Management

The plant disease triangle depicts the three criteria required for a disease outbreak to occur: a susceptible host plant, pathogen presence, and a suitable environment. Host plant resistance or susceptibility to a pathogen and the severity of disease are affected by environmental conditions. Under CEA, environmental conditions can be controlled to eliminate or minimize disease development; however, seed health is important to control pathogen entrance into a CEA system. It is necessary to apply an integrated disease management strategy, including seed treatment (chemo-, physical-, or thermo-therapy), early monitoring and pathogen detection (hyperspectral imaging and machine learning), application of biorational pesticide or biocontrol agents, disinfection and sanitization, and treatment of the water supply system to manage plant diseases in CEA.

Dr. James S. Owen Jr., Research Horticulturist, USDA-ARS, Wooster, OH
CEA Water Quality: Sources, Reuse, and Treatment Challenges for Controlled Environment Systems

Science and industry need to identify resource inefficiencies or limitations to mitigate risk and increase profitability in CEA systems. The agricultural system water cycle includes source water, operational water, and wastewater. An ideal source of water for CEA is non-potable, fresh, high-quality water that is climate resilient and could be supplied from independent sources. Operational water in a CEA system is acidic and mineral nutrient enriched. Operational water should be mitigated or treated for repeated use prior to replenishment to improve facility water use efficiency. Wastewater is non-potable, saline, low-quality water that needs to be directly or indirectly discharged after mitigating potential environmental contaminants. Finding solutions to enable re-use of self-generated effluent/wastewater remains a challenge.

Session 2. Energy Technologies, moderated by Dr. Kale Harbick, USDA-ARS

Roger Buelow, Chief Technology Officer, Aerofarms
Stakeholder Perspective

Aerofarms produces primarily leafy greens in plant factories, using stacked vertical tiers and utilizing LED lighting, aeroponics, and automated nutrient delivery. Sensor data, including machine vision, is used to assess plant health. Aerofarms is pursuing opportunities to expand into production of berries, pharmaceuticals, nutraceuticals, and cosmeceuticals. Research partnerships include several other companies, universities, and government agencies.

Dr. Mike Heben, Professor of Physics, The University of Toledo, Toledo, OH
Controlled Environment Agriculture: Integration of Photovoltaics

Benefits of CEA include increased food security, enhanced climate resiliency, improved resource use efficiency, and local economies. Food-related energy comprised 16% of the U.S. energy budget in 2007. Decreasing costs for solar, wind, and energy storage technologies have been observed. UToledo and ARS previously collaborated on research investigating photovoltaic applications for greenhouses. Improvements in photovoltaic technology include increased efficiency, custom glazing, building integration, adjustability, and retractability.

Dr. Daniel Gerber, Electronic Research Scientist/Engineer, Lawrence Berkeley National Laboratory
Direct Current Microgrids for Controlled Environment Agriculture

Benefits of microgrids in CEA include production resilience (during power outages) and integration of onsite renewables. Most electrical components in greenhouses are natively direct current (DC), including LED lighting, controls, and variable frequency drives in motors and pumps. Using a DC microgrid avoids efficiency losses associated with alternating current (AC)/DC and DC/AC conversions.

Dr. Bruce Bugbee, Professor of Plants, Soils, and Climate, Utah State University
Turning Photons into Food

Spectral quality of light affects both plant growth and development. Different portions of the spectrum have different effects, including photosynthesis, inducing photo-protective compounds, and inhibiting or enhancing cell expansion. Experiments have provided evidence that far red light (from 700 to 750 nm) should be included in the definition of photosynthetically active radiation (PAR) along with the traditionally accepted visible range of 400 to 700 nm. The economics of indoor food production vary heavily with crop type and is affected by market price, harvest index, and lighting energy requirements. It can span the gamut from profitable microgreens (high market price and low energy requirements) to grain crops that are completely infeasible (due to lower market prices and extremely high energy requirements).

Dr. Moon Kim, Research Leader and Research Physicist, USDA-ARS, Beltsville MD
Hyperspectral Imaging

Hyperspectral imaging uses narrow spectral bands over a continuous range of wavelengths and has been utilized at the ARS Environmental Microbial and Food Safety Laboratory since the late 1990s. Research collaboration with NASA is focused on using hyperspectral imaging to aid in plant stress detection and food safety verification in space applications.

Dr. Glenn Lipscomb, Professor of Chemical Engineering, The University of Toledo
Membranes for CEA

Rate-based separations driven by chemical potential differences can be more energy efficient than thermally-driven processes. Membrane technologies reduce operating expenses but can increase capital expenses. Successful applications include desalination and nitrogen gas production. Membranes can be used in CEA to cool and dehumidify air, thereby reducing loads on heating, ventilation, and air conditioning (HVAC) systems, saving energy, and recovering water. The recovered water can then be purified and recycled back into the nutrient system, saving water, and reducing wastewater output.

Dr. Sridhar Viamajala, Professor of Chemical Engineering, The University of Toledo
Algae: Fuel, Food, and Products

Algae comprises a large diversity of single-celled plants and seaweed. Products from algae include biofuels, cosmetics, nutritional supplements, and animal and human food sources. Algae has many potential applications in energy production, wastewater treatment, and CEA. As photosynthetic organisms, algae in photobioreactors absorb CO_2 and sunlight to grow and produce more algae. Research efforts with photobioreactors are focused on more efficient CO_2 uptake, increased yields, and pest mitigation.

Session 3. Social Implications and Systems Analysis, moderated by Defne Apul, The University of Toledo

Peter Fiske, Director of the National Alliance for Water Innovation (NAWI) and Water-Energy Resilience Research Institute (WERRI), Lawrence Berkeley National Laboratory
Water Treatment

The water-related vision for CEA could resemble a water machine, which looks less like a wastewater treatment plant and more like pool and spa packaged technology that operates to treat and recycle water in CEA. It would be modular and easy to maintain. Water-related challenges for CEA that will require research include measurement and adjustment of water chemistry for fertigation, humidity control and optimization, pathogen control (fungi, viruses, etc.), solute accumulation, nuisance biofilm formation, data management, and systems optimization.

Dr. Youngwoo Seo, Professor of Chemical Engineering, The University of Toledo
Water Treatment Issues

Biofilm accumulation and microbially healthy water are unique considerations in many CEA water systems due to high water temperatures, high concentrations of biodegradable organic matter and nutrients, requirement of a closed loop nutrient recycling system, expected high surface area-to-volume ratios, and sometimes stagnant water conditions. Biofilm can become a source of pathogens in the irrigation systems. Biofilm can clog drippers or sprayers directly by growing on them, or indirectly when detached clogs coagulate in small diameter tubes or nozzles. Biofilm can cause an uneven supply of nutrient solution to the crop within the greenhouse. Several biofilm-related issues to be considered in CEA include using direct chemical treatment to remove existing biofilms or prevent future biofilm outbreaks, exploring low frequency electromagnetic fields or ultrasound treatment for CEA systems, evaluating antimicrobial coatings for irrigation lines, using point-of-use UV disinfection or ozone systems for source water treatment, using beneficial biofilms to control problematic biofilms (probiotic approach), and understanding interspecies interactions (quorum sensing) to minimize biofilm formation.

Arman Shehabi, Research Scientist and Project Leader, Lawrence Berkeley National Laboratory
Costs and Environmental Metrics

The basic concepts of life cycle assessment (LCA) and techno-economic analysis (TEA) were presented, highlighting the need for cross-sector analysis. As CEA replaces other systems, what will its effect be across different sectors and in aggregate for the whole supply chain? Complex systems modeling combined with LCA, and TEA could be used to evaluate CEA. These types of approaches would show fundamental differences in the inputs and outputs for field-based agriculture vs. CEA. Advantages of CEA include a smaller land footprint (enhanced in indoor farms by stacking multiple levels); high efficiency water reclamation; lower fertilizer use due to water reclamation; lower pesticide use due to water reclamation and growing in a controlled environment; higher yields due to a controlled climate, supplemental light, and CO_2 enhancement; and a fresher product with less food waste due to proximity to consumers. The disadvantages of CEA are higher energy costs; increased automation and repair costs; higher land costs due to proximity to consumers; increased indirect CO_2 emissions; and criteria pollutant emissions from higher energy consumption.

Jennifer Stokes-Draut, Research Scientist, Lawrence Berkeley National Laboratory
Spatial Planning Issues

Where will CEA be located? The answer will depend on local climate conditions that vary drastically across the U.S. Climate change may affect decisions about CEA locations as crop yields will increase in some regions but decrease in others. Other relevant parameters include the demand for local food, food waste production, addressing food deserts, and improving food supply chain resilience, all of which vary across the U.S. The cost of produce from CEA will also depend on location since labor, delivery, equipment, structure, and utilities that affect the cost of produce vary spatially. If CEA were to be implemented in Toledo, for example, they could be located in food deserts and in brownfield sites close to other industries and wastewater facilities where combined heat and power (CHP) or other resource sharing could occur. Produce cost will also depend on the economies of scale and learning curves for relevant technologies. Based on other studies, costs will decrease with larger facility size and with greater experience.

Sabine O'Hara, Distinguished Professor & Ph.D. Program Director, University of the District of Columbia
Environmental and Food Justice

The global food production system has a significant environmental impact. Eleven percent of U.S. greenhouse gas emissions, and 25% of CO_2 emissions worldwide, stem from food transportation; 70% of global freshwater is used in agriculture; and 30% of food production is wasted. Current global food production practices also have negative social externalities, including food insecurity and preventable nutrition-related illnesses (diabetes, hypertension, obesity), which translate into increased vulnerability to other shocks. Environmental and social externalities of food production depend on the length of the supply chain. For example, food delivery to homes has a long supply chain compared to sourcing food from a backyard garden or farmer's market. Some externalities are unavoidable since some people do not have access to home food delivery or a farmer's market. Externalities also depend on geographical location and socio-economic factors like household income, employment status, gender, and race and ethnicity. At the core of the problem is that the value of people and nature is reduced to inputs. A way to avoid this problem is to not consider environment, society, and economics as equal concepts, but rather to use a conceptual model that embeds the economy within society, which then is embedded within the environment. This is a strong sustainability model in which society and the economy operate within the constraints of the environment. Ultimately, we should seek to create a restorative food system that improves public health, alleviates disparities, produces at least some food local to most consumers, uses less energy, produces fewer greenhouse gases, reduces water use and food waste, restores ecosystem services, and reconnects people with nature. To achieve this, we must rethink the role of our institutions.

Anjuli Jain, American Association for the Advancement of Science (AAAS) Science Technology and Policy Fellow, Department of Energy
DOE Environmental Justice

Environmental justice can be thought of as a four-pillar model that includes procedural, recognitive, distributive, and restorative justice. Environmental justice implications will depend on the scale and goals of CEA. A small-scale system could be represented by a plug-in home kit; it would be a distributed, bottom-up, amateur, specialized market that is hyper-local and has a small production. An example of a large-scale system is an industrial plant factory that has a centralized, professional, general market with a distribution system and larger food production. CEA's promises and risks will vary across the four pillars of environmental justice. Some environmental justice topics to consider include ensuring that historically underserved communities have access to financial and technical programs and services within CEA systems; ensuring the scale of CEA enables the stated goals (food security, nutrition); considering who is included in the process, what is grown, who benefits, what is the full cycle of inputs, and who is helped, displaced or hindered; recognizing who is fed by the food produced in CEA; understanding who takes on the burden of the energy production and costs; and recognizing whether CEA is entrenching existing patterns that hinder advancement of environmental justice DOE's Justice 40 program aims for federal investments to be made such that 40% of the overall benefits flow to disadvantaged communities.

Gioia Massa, Project Scientist, NASA
Tech Transfer: Behavioral Factors

This session discussed NASA's research into the impacts of space crop production on astronaut behavioral health. A questionnaire was given to eight crew members during their tour aboard the International Space Station. Participants reported that interacting with crops was engaging and meaningful work. This engagement had a positive impact on mood, well-being, and relationships with crewmates. It provided a positive source of sensory stimulation and enhanced their subjective connection to Earth.

III. Research Themes

MICROBIOMES

Discussion summary

The CEA microbiome includes all microorganisms (fungi, bacteria, oomycetes, viruses, and protists) in CEA production systems. These microorganisms may be beneficial, neutral, or pathogenic. Understanding these microbiomes is critical to improving CEA productivity and sustainability. Much of past microbiome research has focused on root-associated microbes present in soilless substrates or hydroponic water films surrounding plant roots, as these root-associated microbes directly influence plant growth and health. Microbes in irrigation water, water channels, plant leaf and fruit surfaces, and air also affect plant health. Beneficial microbial communities in any of these sites promote plant health by improving nutrient uptake, providing protection from plant pathogens, or mitigating plant stresses. The microbiome also includes functional organisms that mediate nutrient cycling, organic matter decomposition, and aeration. Microbiomes in CEA also include plant and human pathogens that are deleterious to plant health or humans that ingest them. The plant and soil microbiome influences plant health and nutritional content, which are intrinsically linked to human health and the gut microbiome, although exact linkages are still poorly understood.

New DNA and RNA sequencing tools, including high throughput amplicon sequencing or metagenomic techniques, allow scientists to identify, quantify, and assign function rapidly to the broad range of microbial species associated with horticultural crops, soils, or substrates. Prior to the introduction and adoption of these sequencing tools, a single microbial genus or species was screened laboriously to determine its effects on plant health or suppression of plant pathogens. Now scientists can identify and catalog the presence and function of thousands of microbes simultaneously to better understand how the entire microbial community interacts with plants, the environment, and each other, and ultimately how that impacts crop health and quality. High throughput sequencing approaches complement traditional microbial screening approaches and can speed the discovery and application of beneficial microbes. Native microbiomes can be conditioned in CEA systems to improve plant health and productivity, and new sequencing approaches will allow scientists to characterize microbiome shifts that occur due to grower management practices.

Critical needs and research:

- How can CEA microbiomes be controlled to maximize productivity and improve sustainability?

Table 1: Challenges, needs, and opportunities in the Microbiome theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
Understand microbiome dynamics in CEA to control pathogens.	3.92	0.27	26
Understand how different crops recruit and maintain root microbiome in CEA systems.	3.69	0.26	26
Understand molecular mechanisms of how soil/rhizosphere microbiome enhances crop health, productivity, and ecosystem health (increased carbon storage, decreased greenhouse gas production, decreased nitrate leaching/water contamination from ag fields, promoted biodiversity).	3.67	0.30	27
Understand how the microbiome affects aspects of wellness in plants and the animals or people who consume them.	3.57	0.30	23
Understand the inherent microbial populations in CEA systems to support plant health and whether microbes need to be supplemented via seed or nutrient solutions.	3.33	0.34	24
Understand the functionality of the natural microbiomes as they occur in field conditions, and incorporate them in CEA systems for exploitation in reclaiming energy, water, carbon sequestration, etc.	3.19	0.32	26

Table 2: Research questions in the Microbiome theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
How can CEA microbiomes be manipulated to suppress pathogens, promote plant health, food safety, and food quality?	4.33	0.20	18
How can CEA microbiomes be manipulated to increase crop yields and health and also promote ecosystem services (reduce greenhouse gas production, increase carbon sequestration, reduce water contamination)?	4.00	0.29	18
How is the nutritional content of crops impacted by microbes? Can probiotics be used to make CEA crops more nutritious vs. conventional crops?	3.75	0.28	20
Is there a hidden seed microbiome? Can biocontrol enhance the management of pests/pathogens carried in seeds?	3.65	0.28	17
Sanitation also eliminates beneficial microbes, reduces microbial diversity and can result in reduction of plant resilience. Are there approaches to eliminate pathogens in a more targeted manner?	3.53	0.29	17
Are functions embedded in the intrinsic microbiomes that can be exploited to enhance CEA efficiency and outputs?	3.53	0.29	17
Are amended microbiomes stable over time?	3.44	0.22	16

PESTS, DISEASES, AND BENEFICIALS

Discussion summary

With enclosed structures and controlled environments, fewer opportunities exist for introducing exotic pests and diseases into a CEA cropping system. However, seedborne pathogens and mechanically transmitted diseases have caused serious concerns for CEA vegetable growers. For crops with a long growing season (e.g., tomatoes, peppers, and cucumbers), intensive cultivation and frequent plant handling can spread disease quickly, resulting in a serious outbreak. With increasing global seed trade activities, any emerging seedborne pathogen with resistance to traditional control measures could potentially cause a serious disease outbreak world-wide (e.g., tomato brown rugose fruit virus in greenhouse-grown tomatoes). With fewer chemical control options available for CEA crops, biological beneficials are often introduced to manage some pests (e.g., whiteflies). Breeding for disease resistance using marker-assisted selection or application of biotechnology, including gene editing, would speed the development of novel genetic materials with resistance.

Critical needs and research:

- What opportunities exist to develop new cultivars with pest and disease resistance that are suitable for CEA through speed breeding and biotechnology, especially gene-editing technologies?
- What new seed treatments are effective for managing major seedborne pathogens in CEA?
- How can we develop biological control agents and chemotherapy measures that can be used to manage major pests and diseases on CEA crops?
- What are new open plant pathology approaches to promoting plant health within and across the CEA industry?

Table 3: Challenges, needs, and opportunities in the Pests, Disease, and Beneficials theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
Developing pest and disease resistance cultivars (as well as rootstocks), particularly emerging diseases, through innovative genetic selection and breeding suitable for CEA production.	4.12	0.27	26
Biotechnology (e.g., RNAi and gene editing) has great potential due to genome sequence information available for a number of CEA crops; however, there is a need to build better channels of communication between the researchers and growers so that industry needs and concerns are addressed.	3.73	0.26	26
Incorporate steps to enable seed treatment, probiotic and prebiotic, and other biocontrol agents that can inhibit pests and pathogens and enhance yield, quality, and nutritional content of pesticide-free products.	3.71	0.30	27
CEA is generally a monocrop production. This leads to the need for high levels of knowledge and testing on chemotherapy (disinfectants, ozone technology, UV irradiation, etc.) on seeds, plants, and surfaces to manage emerging virus, bacteria, and other challenging mechanically transmitted pathogens.	3.71	0.30	23
Open plant pathology approaches within industry to promote plant health across the industry. As we have seen with COVID, we need to work together to address disease issues as a broader community.	3.35	0.34	24

Table 4: Research questions in the Pests, Disease, and Beneficials theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
What systems can be developed for early detection and management of pests and diseases?	4.12	0.22	17
Can integrated pest management systems be developed to control pests and diseases relative to food safety, including seed treatment and sanitization on workers, plants, and surfaces for virus and other mechanically transmitted diseases?	3.82	0.25	17
Can disease-resistant cultivars be developed through breeding and biotechnology (RNAi and gene-editing)?	3.76	0.30	17
Can knives used for harvesting and plant training be developed that do not transmit diseases, including viruses and other pathogens?	3.58	0.30	12
Can we develop a public-private working group to address plant health issues in CEA?	3.53	0.24	17
How do we investigate different effectors and the roles of beneficial microbes and modify them to use in crop productivity and disease resistance?	3.35	0.26	17

ENERGY EFFICIENCY

Discussion summary

Commercial and residential buildings have made strides toward net-zero energy consumption with two key steps: improving energy efficiency through conservation and utilizing renewable energy sources. These principles can be applied to CEA systems as well. More sophisticated lighting, HVAC, and CO_2 controls have large energy-saving potential. Innovative designs can increase lighting uniformity, improve production consistency, and conserve energy.

Most greenhouses use a legacy lighting technology, high-pressure sodium (HPS) lamps, that usually consumes more energy than newer light emitting diode (LED) fixtures. LED lighting is considerably more energy efficient than just a few years ago. Continuing to improve the efficacy of LEDs, especially in the green part of the spectrum (known as the "green gap"), is important, although the laws of physics dictate the upper limits in additional efficiencies that can be gained using current technologies. Lighting energy can also be reduced by improving control systems and building designs to maximize natural light availability in greenhouses. Researchers are exploring spectral tuning and pulsed frequency lighting to see if energy consumption can be further reduced while maintaining production standards. Plants require less light to get the same yield when the indoor or greenhouse environment is supplemented with CO_2, which is favorable from a carbon footprint standpoint (the reduction of electrical lighting is much greater than the increase from supplementation itself) but requires proper controls to use effectively. There is a need to measure leaf, plant, and whole system net CO_2 flux. Outside the facility, transportation energy and carbon footprint are large for outdoor field crops that may be hundreds or thousands of miles away from market. Urban plant factories and peri-urban greenhouses reduce this footprint considerably.

When energy-efficiency improvements have reduced electricity loads sufficiently, renewable energy sources, such as solar, become much more feasible. Unlike very efficient residential and commercial buildings that can be powered by rooftop photovoltaics (solar panels) alone in some cases, CEA facilities would require a photovoltaic array footprint many times larger than the building's footprint due to the large amount of energy required to grow plants and the high plant density achieved with multi-tier shelving. Therefore, minimizing energy consumption is an important first step before utilizing renewables. Commercially available and emerging technologies that may improve building envelope performance, by reducing solar heat gain and reducing energy loads, include coatings, transparent insulation, dynamic glazing, integrated photovoltaics, and highly insulating [hi-R] window technologies.

Industrial synergies can be explored to improve energy efficiency in CEA. Co-locating a CEA production facility near a CHP plant is a common practice in Europe and has great potential in the U.S. as well. It has significant potential to reduce the carbon footprint and energy consumption of CEA, as CHP plants produce a large amount of waste heat and CO_2 that could be directly utilized in CEA for crop production.

Plant factories use a large amount of energy to dehumidify using mechanical cooling systems, as opposed to greenhouses which primarily use roof or side-wall ventilation. Advancements in heat recovery, economizers, desiccants, membranes, and other HVAC innovations will help reduce this load. Direct current microgrids offer energy-saving potential since most electrical equipment used in CEA runs on DC and converting back and forth to AC incurs efficiency losses. This will become more pronounced as more onsite renewables, such as photovoltaics, are incorporated into CEA facilities.

Finally, energy costs may be reduced independently of conservation by using more sophisticated sub-metering and rate structures, if offered by local utilities and if control systems are sophisticated enough to utilize the information.

Critical needs and research:

- How can we accurately model and reduce CEA energy consumption?
- What renewable generation technologies make sense for CEA?

Table 5: Challenges, needs, and opportunities in the Energy Efficiency theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
Increase investments in HVAC to better utilize light and waste heat.	3.96	0.27	26
Increase investments in lighting to provide better control of natural/supplemental light, minimize non-photosynthetic light, and optimize intensity, wavelength, and pulsing.	3.81	0.26	26
Develop an energy simulation tool for CEA, possibly integrated with existing tools.	3.57	0.30	23
Develop electricity infrastructure by utilizing storage, renewable generation, demand response, and DC microgrids.	3.57	0.34	24
Increase investments in windows and other building envelope components, such as coatings to reduce solar heat gain.	3.46	0.32	26
Integrate CEA and other infrastructure, such as office buildings, CHP, cement plants, and bioethanol plants.	3.20	0.31	26
Need to measure leaf, plant, and whole system net CO_2 flux.	3.58	0.32	26

Table 6: Research questions in the Energy Efficiency theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
How can thermal and optical properties of a CEA building envelope be optimized?	4.19	0.31	16
How can natural and supplemental light be optimized with respect to wavelength, pulsing, intensity, fiber optics, and distribution?	4.18	0.21	17
How can a "closed" greenhouse be made practical with no water loss other than to food and no heating/cooling through air exchange?	4.00	0.26	22
How can CEA thermal loads be optimally integrated with other infrastructure, such as power plants/CHP, co-located industry/other activity, or heat pumps?	3.89	0.24	19
Is photosynthesis without light possible?	3.13	0.35	15

WATER AND WASTE MANAGEMENT

Discussion summary

The economic viability of CEA depends strongly on optimizing water use to reduce operating costs. Ideally, all water that enters a CEA facility would leave in the plants produced and the facility would produce no wastewater. Moreover, no plant nutrients or chemicals used to enhance growth would leave either in wastewater or solid waste streams. The ideal CEA facility has only one output — plants.

Water management was ranked among the top five concerns and research questions of workshop attendees. While CEA uses 5% to 10% of the water used to produce field crops, water consumption and loss of nutrients and chemicals remain problematic.

Improving water treatment, reducing biofilms, and increasing the use of algal farms highlight opportunities for addressing water use concerns. The wide spectrum of processes developed for municipal/industrial wastewater treatment and desalination, primarily membrane and biologically based, are available for immediate adoption for CEA. However, the design of a CEA water treatment system will differ significantly from municipal and industrial applications due to system size. Use of modular, low-cost components will be critical. For example, the Hydraloop is a commercially available, TRL-9 water recycling system designed for household municipal reuse for non-potable purposes; something similar could be designed for CEA.

Biofilms can arise in all water treatment and distribution systems. While biofilms can be used for waste degradation, they can also harbor waterborne pathogens and clog pipes and nozzles, both of which can be detrimental to CEA operations. Several strategies exist for biofilm control, such as antimicrobial treatment, UV or ozone disinfection, use of probiotics, and use of disruptive external fields. Increasing the efficacy and cost effectiveness of these treatment options, as well as developing strategies tailored to CEA facilities would enhance production and profitability for growers.

Algae production offers an alternative to mitigate wastewater production. Nutrients and chemicals in wastewater are used by the algae for growth. The algae, in turn, can be converted into a variety of products, including fuels and materials. Integrating algal bioreactors into CEA facilities and improving their feedstock efficiency are ongoing areas of research.

Concerns were expressed over the cost of water treatment, especially high-tech alternatives, and system readiness for deployment. Optimism existed for potentially achieving zero wastewater discharge with recovery of all wastewater components for recycling. Tailoring a wastewater system for geographical location, water source, and the microbiome is important. Additionally, integrating water management with heating/cooling offers an opportunity to reduce water losses from sources other than the plants produced.

Resource consumption and waste reduction opportunities were suggested through use of soilless culture. Additionally, attendees promoted the goal of pesticide- and fertilizer-free production.

Critical needs and research:

- Can CEA be operated with zero wastewater discharge?
- What is the impact of biofilm formation in CEA and how is it best mitigated?

Table 7: Challenges, needs, and opportunities in the Water and Waste Management theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic			
Precision water treatment systems are needed to reclaim nutrients and chemicals in wastewater for reuse.	4.11	0.27	26
Reclamation of wastewater, including use of bioremediation, is an opportunity.	4.08	0.26	26
Managing irrigation systems well to avoid cross-contamination or biofilm formation is a challenge.	3.72	0.30	27
Strategies to achieve zero waste discharge are needed that help: ■ reclaim water from HVAC systems, ■ reduce water use (soilless culture or management), ■ optimize mineral nutrient inputs, ■ optimize productivity via microbiome and fertilizer, ■ minimize pesticides/use rapidly degradable pesticides, ■ treat wastewater for reuse (physio- chemio- bio- phyto- remediation), and ■ address the impact of local water quality on operation.	3.65	0.30	23
The use of HVAC condenser water poses significant challenges, especially with the need for biofouling control.	3.57	0.34	24
Alternative soilless culture/substrate methods are needed to reduce resource utilization.	3.54	0.32	26
Methods are needed to characterize biological properties, electrochemical properties, and metal concentrations of wastewater to achieve zero discharge operation.	3.48	0.31	26
An opportunity exists to reduce costs and environmental footprint through pesticide and fertilizer-free production.	3.44	0.29	26
Numerous opportunities for waste reduction exist through control of CEA production to: ■ increase crop WUE and decrease water footprint, ■ reduce water vapor loss (coupled with energy recovery), ■ control of biofilm formations, and ■ use of culture microbiome to increase resource utilization.	3.42	0.26	24
We need better utilization of alternative water sources including: ■ commercial or agricultural sources, and ■ surface runoff from facility rooftop and/or from surrounding commercial, industrial, agricultural areas, and ■ utilization also needs better characterization of water quality.	3.39	0.27	24
An opportunity exists for commercial, agricultural, or industrial partnerships that optimize local water utilization.	3.23	0.32	23
A need exists for microbiomes that increase nitrogen utilization efficiency and decrease nitrogen leaching from soil during plant growth.	3.13	0.20	26
Water is essential to life and providing clean, safe water for human consumption is a challenge.	3.00	0.24	23

Table 8: Research questions in the Water and Waste Management theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
How can we achieve zero discharge operations? ■ How do we utilize less water (soilless culture alterations, alter flow, close water cycle, etc.)? ■ What CEA innovations can be used to minimize water consumption in water scarce areas? ■ How do we develop use for discharge water from CEAs? ■ How do we most effectively, including cost, treat water (internally and externally) to increase water and environmental stewardship? ■ How do we incorporate alternative water sources (to reduce potable, groundwater use) and optimally recycle multiple alternative water sources in CEA?	4.38	0.24	21
How do the microbiome, agrichemicals, and metals influence internal water reuse? How best to treat wastewater and reduce environmental impacts?	3.80	0.19	20
Can water be treated passively in existing CEA operations without adding additional infrastructure?	3.42	0.25	19
Can bioremediation assist wastewater management systems?	3.33	0.21	21

SENSORS AND TESTBEDS

Discussion summary

Sensors can provide a wealth of information on environmental conditions and plant health status but can increase the capital and operating costs of facilities. Resulting data sets are large and complex enough that technologies for machine learning, edge computing, and big data should be utilized to glean meaningful patterns and information from them.

Light modeling for commercial buildings depends on assumptions such as far-field approximation and Lambertian sources. These are often suitable for greenhouse applications but not for stacked plant factories. In near-field applications, new measurement systems for characterizing horticultural light output are required. The energy efficiency of horticultural lights is difficult to independently verify and requires specialized equipment such as an integrating sphere and power analyzer for quantification.

Multi-spectral and hyper-spectral imaging systems are becoming more affordable and provide new options in early disease detection and assessing water stress. Challenges exist in mounting and deploying imaging systems in greenhouses and indoor plant factories for autonomous measurement of the plant canopy, where obstacles such as building infrastructure and the minimal space between vertical stacked layers currently hinder their application.

Primary research that investigates correlations and causal relationships between environmental conditions and plant health, yield, and morphology is difficult and time-consuming work, and often varies with species and cultivar. For example, the effects of different wavelengths of light on plant growth and shape are known for some cultivars, but combinations of wavelengths can have entirely distinct effects, and other cultivars may respond differently.

Desired innovations in sensor technology include ways to assess flavor in fruits and vegetables, thermal and fluorescence imaging, machine vision, environmental conditions, artificial intelligence, robotic portable gas exchange sensors, disease effects, and food safety.

Critical needs and research:

- What will be the next generation of sensors and what data will they provide which current sensors cannot?
- How can machine learning and big data be utilized to improve CEA production?

Table 9: Challenges, needs, and opportunities in the Sensors and Testbeds theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
Integrate hyperspectral imaging showing reflectance and fluorescence with artificial intelligence (AI) to aid in plant health and food safety monitoring.	4.00	0.27	26
Utilize machine vision and AI systems to assist with harvesting and track plant health and pest pressure.	4.00	0.26	26
Develop tools to evaluate flavor of fresh fruit and vegetables.	3.79	0.30	27
Develop sensors and online monitoring of trace volatile organic compounds or other signals including natural and stress emissions for early detection of disease or abiotic stress.	3.76	0.30	23
Develop controlled ecosystems that mimic field conditions to test phenotypes of bioengineered plants, beneficial microbial inoculants developed in the lab and provide platforms for rapid development of microbiomes beneficial for plant and environment.	3.50	0.34	24
Develop robotic portable leaf photosynthesis systems to automatically measure gas exchange under environmentally controlled conditions.	3.48	0.32	26

Table 10: Research questions in the Sensors and Testbeds theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
Can we integrate automation, hyperspectral imaging, and machine learning to optimize plant growth and nutrition with respect to light, media, probiotics?	4.40	0.25	20
Can more intelligent controllers be developed for lighting using existing light, CO_2, and temperature models?	4.24	0.16	17
How can sensing variables be identified and prioritized for optimal plant growth such as light intensity, color, and water conductivity?	4.15	0.18	20
How can nutrient profiles, bioactive compounds, and microbiomes be assessed with the understanding that food is produced to nourish people and animals?	3.57	0.30	23
Are there sufficient microbial populations in CEA systems to support plant health or do microbes need to be introduced with seed or nutrient solutions?	3.33	0.34	24
How can the functionality of natural microbiomes be understood as they occur in field conditions, and be incorporated in CEA systems to reclaim energy and water, or utilize carbon sequestration?	3.19	0.32	26

ENVIRONMENTAL SUSTAINABILITY

Discussion summary

The environmental implications of food production are quite large, as noted particularly by workshop speaker Dr. Sabine O'Hara (see her presentation summary for statistics). Some experts predict CEA will have lower environmental impacts than field-based food systems due to the smaller land footprint (enhanced by stacking multiple levels), a higher efficiency, and lower fertilizer and pesticide use in a controlled and closed environment. CEA could have higher yields due to controlled climate, supplemental light, and CO_2 enhancement. Additionally, CEA could decrease food miles and food waste and provide consumers with access to fresher product. On the other hand, CEA may increase environmental impacts due to higher energy use and the associated upstream and direct emissions of CO_2, among others. Environmental implications, like financial costs, may be affected by location (e.g., available sources of energy), design, and economies of scale, though the magnitude is not known.

CEA incorporates a variety of technologies, and every technology involves economic and environmental tradeoffs that should be considered in the design process. The costs and environmental implications of integrating with existing infrastructure will vary. CEA would benefit from an integrated system design tool that enables component evaluation to better evaluate the ideal combination of different technologies to achieve the preferred balance in cost effectiveness, efficiency, resiliency, and sustainability. Answering this will require a large amount of data, much of which should come directly from the industry. Committed industry partners will be critical to achieving this outcome.

Ideally, this complex system modeling will incorporate LCA and TEA to understand the environmental and cost tradeoffs. These tools can be used to quantify baseline metrics (e.g., plant productivity, energy and water efficiency, carbon footprint, cost/acre) that will need to be exceeded for CEA to be competitive in different regions. Equally important, they can quantify externalities (both positive and negative) and hidden subsidies, including the cost of transporting produce across the country (fuel, cold chain); the health and environmental costs of widespread pesticide, fungicide, and herbicide usage; and the cost of subsidizing agricultural water usage. These considerations are critical to better compare CEA to field-based agriculture.

In TEA and LCA, the entire food chain, from farm to table, should be considered, and a cross sector analysis should be incorporated into modeling scenarios that estimates the supply chain effects of CEA replacing field-based systems. The need to integrate CEA with an evolving energy sector that includes renewable energy, CHP, district energy, and microgrids should be addressed. Sustainable alternatives to common materials should also be modeled (e.g., to be more environmentally sustainable, the industry can reduce its reliance on products such as rockwool, plastics, and perlite and develop biological-based, biodegradable alternatives). These new products can be modeled using LCA. While LCA and TEA are fairly well-developed methodologies, some modeling challenges may arise with CEA because facilities are smaller and more decentralized than conventional systems.

Critical needs and research:

- How can we design and operate CEA so it is more economically and environmentally more sustainable than conventional systems?
- What are the baseline metrics that must be exceeded to make CEA competitive?
- What are the effects of geographical location, size, and technology integration?
- How does the explicit consideration of externalities impact overall assessment?
- How can we develop and use complex system models like LCA and TEA to evaluate the above questions?

Table 11: Challenges, needs, and opportunities in the Environmental Sustainability theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic			
Data needed to assess these questions is going to be hard to gather and may limit what we learn. We need committed industry partners.	4.05	0.27	26
Need better quantification of CEA sustainability by incorporating negative and positive externalities of CEA and hidden subsidies of the field, like the cost of transporting produce across the country (fuel, cold chain), the health and environmental costs of widespread pesticide, fungicide, and herbicide usage, and the cost of subsidizing agricultural water usage so we can compare to field-based agriculture better.	4.04	0.26	26
It is essential that the entire food chain energy, carbon footprint, sustainability, and resilience for CEA vs. field farming be demonstrated, including use of renewables and CHP including decarbonized fuels.	4.03	0.30	27
Opportunity to build better estimation tools. Existing models like LCA may not fit in well for CEA due to smaller scale and more decentralized operation of CEA. Also, CEA may shorten supply chains and possibly create social cohesion and increase resilience. These are factors not typically included in environmental sustainability metrics.	3.77	0.30	23
Need to consider systemic impacts, including integration with CHP, district energy, and microgrids.	3.75	0.34	24
Reduce reliance of industry on products such as rockwool, plastics, and perlite. Develop biological-based, biodegradable alternatives.	3.52	0.31	26
Perform LCA of CEA and food supply chain from greenhouse to table while assessing data availability.	3.58	0.30	27

Table 12: Research questions in the Environmental Sustainability theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
What are the baseline metrics (e.g., plant productivity energy efficiency [% improvement?], water efficiency, cost/acre) that need to be exceeded to make CEA competitive? How do these metrics vary across regions?	4.32	0.19	22
Do we need a focused, integrated system design tool that also enables component evaluation from energy use, emissions, and economics perspectives?	4.16	0.23	19
What are the best technology integration strategies (which technology, how, for which context) for designing efficient, resilient, and sustainable CEAs? In other words, how can we improve the design process to better evaluate the tradeoffs for integrating different types of technologies? How can we create both resilient and sustainable physical infrastructure to support the new agricultural technologies?	3.90	0.28	21
What are the prospects for CEA to reduce the land area needed for agriculture generally, to free up space for native species habitats? Realizing to make much difference, this will need to focus on cereal crops. Is there any path that researchers can currently see to making this cost-effective enough (perhaps with incentives paid to free up land for conservation) for at least some significant portion of global crop production — even a few % would be a tremendous win.	3.50	0.36	22
How to elongate the shelf life of tomatoes and other crops produced in high volumes in CEA? Is there enough immediate demand? Are surplus volumes directed to secondary products? Are surplus volumes causing additional greenhouse emissions?	3.32	0.23	19
Can we develop small scale direct air capture (DAC) technology systems that can leverage CEA as their carbon sink.	3.26	0.29	19

SOCIAL SUSTAINABILITY

Discussion summary

By 2040, we will have nine billion people on Earth to feed and consequent social challenges in feeding this population. Social sustainability impacts (e.g., justice, food safety, nutrition, labor, workforce training) should be addressed up front in the development of CEA systems. Well-planned CEA may be able to create a restorative food system that improves public health, alleviates disparities, offers low investment alternatives, improves environmental justice, and reconnects people and nature, but we need to carefully consider the role of our institutions, who is included in the decision-making process, who benefits, and who is displaced or experiences other negative effects as a result of CEA production.

There are many examples of social sustainability considerations for CEA. For instance, communities with high food insecurity often have low financial and technical resources; CEA should address these needs. As CEA shifts how the food and energy sectors interact, we will need to address who will take on the burden of energy production and costs and whether CEA will shift or entrench existing patterns. Equitably managing the impact CEA will have on the labor market needs to be considered. Traditional land farmers are an integral part of rural communities and may be at a competitive disadvantage as investment in CEA grows. CEA may transition field labor in rural communities to factory employment in cities, negatively impacting traditional farmers; however, this may be balanced or mitigated with the creation of new jobs that export fresh and processed food from urban and peri-urban CEA sites to rural areas.

Climate change will affect where agriculture occurs. CEA could protect jobs and communities in some areas as weather conditions change. Like many industries, automation will replace some labor needs in CEA and more skilled and technologically savvy positions will be created. Therefore, while exact shifts in jobs and their geographical locations have yet to be determined, it is possible that the overall labor demand will reduce, negatively impacting the labor market.

Growth in the demand for locally produced food in CEA is consumer-driven, not always based on economics but more on emotions. CEA would ideally be developed not only for high revenue markets but also for local production for underserved populations. Identifying business models that address both the need for food security and revenue ought to be examined.

Growing plants in CEA affects the nutritional, flavor quality, and storability of produce. In the current food system, transport resilience and a long shelf life are prioritized. As CEA expands its footprint in the food system, priorities may shift to quality and optimal ripeness of local food. Public acceptance for genetically engineered crops may also change as these crops become available for growers to use in CEA systems and provide trait improvements desired by consumers.

To evaluate the social sustainability of CEA, metrics are needed to assess the direct economic, social, and environmental impacts of CEA but also its indirect and induced impacts stemming from its connections to other sectors of the economy that deliver inputs and offer processing and distribution links.

Critical needs and research:

- How can CEA be designed and operated to improve social impacts such as justice, food safety, nutrition, labor, workforce training?
- How can we assess each social impact such as justice, food safety, nutrition, labor, and workforce training?
- How can we better understand who is included in the CEA process; who benefits from CEA production; and who is helped, displaced, or hindered by CEA?
- How can CEA address the needs of low financial and skills resources communities?

Table 13: Challenges, needs, and opportunities in the Social Sustainability theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
How can CEA focus on local production for underserved populations rather than high revenue markets? What is the business model that addresses both food security needs and revenue needs? How will CEA address the needs of low financial and skills resources communities?	4.00	0.27	26
The economics of CHP - CEA may depend on monetized incentivization of other attributes of CEA (e.g., food resiliency, food justice, food quality to disadvantaged urban area, local community electric power resiliency, reduced stress on water treatment facilities, reduced environmental stress on regional watershed [e.g. Chesapeake Bay Watershed], etc.). How do these interact?	3.76	0.26	26
Training and education needs for CEA are huge both on the technology and the agriculture side. As an example, urban populations interested in CEA have very limited agricultural background but may have a strong tech background. For other populations, it may be the opposite. Bridging these training gaps will be a significant challenge. How is the CEA community working with the traditional land farmers? Is there some communication to help existing farmers even transition to CEA without putting them and their communities at a disadvantage?	3.75	0.30	27
How does urban food access through urban farming change the relationship of urban residents to fresh produce?	3.68	0.30	23
Since the biggest advantage of growing plants in layers (indoor agriculture) is the reduced labor input, what is the social cost to the labor market? Like so many other things in society, we are substituting energy for labor. Can CEA be a means of protecting jobs and communities in some areas as conditions change?	3.48	0.34	24
Is there potential for greater public acceptance for GM crops if they are grown in CEA systems?	3.42	0.32	26
Food production is a national security issue, labor is the biggest hurdle.	3.33	0.33	12
For CEA to work well, an electricity export tariff that the CHP-CEA facility can expect for exporting electricity from on-site CHP to the central grid system is needed. Incentives — and the risks of those changing - matter.	3.18	0.31	26

Table 14: Research questions in the Social Sustainability theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
How will CEA affect fruit nutritional and flavor quality, and storability?	4.29	0.23	21
What is the national health benefit associated with better (we assume) food safety and change (either direction) in nutritional value and access through CEA?	4.06	0.28	18
What workforce training is needed to effectively transfer our new innovations into the industry?	4.05	0.22	19
Can a shift to locally sourced CEA produce shift the priorities from produce transport resilience and shelf life toward quality and optimal ripeness?	4.00	0.26	21
Do consumers want to purchase or consume these products?	3.90	0.24	20
How will CEA impact the number and quality/safety of jobs in agriculture and supporting industries? How can we support labor transitions needed?	3.90	0.19	20
How do we identify the communities that need CEA the most and how do we engage with them?	3.76	0.28	21
What metrics will we develop to not only assess the direct economic, social, and environmental impacts of CEA but also its indirect and induced impacts stemming from its connections to other economic sectors that deliver inputs, and offer processing and distribution links, etc.?	3.76	0.28	17
How do we ensure equitable transition of field labor to factory employment?	3.70	0.23	20
Can processed food items linked to CEA generate job opportunities and/or create continuity of operations capable of exporting outputs to rural areas?	3.60	0.27	20
How to elongate the shelf life of tomatoes and other crops produced in high volumes in CEA? Is there enough immediate demand? Are surplus volumes directed to secondary products? Are surplus volumes causing additional greenhouse emissions?	3.17	0.25	18

GENETICS

Discussion summary

The current plant genetics and breeding efforts for vegetable crops are mainly designed to serve open-field production methods. With increasing business growth and new technology development for the CEA industry, more vegetable and small fruit crops are being produced under controlled environment conditions; however, the genetic potentials for crop yield, quality, flavor, nutritional content, and plant architecture under controlled environments have yet to be fully explored. There is enormous potential for greater use of the public USDA plant germplasm resources. Speed breeding facilitated by controlled environment conditions can expedite the breeding process to develop new cultivars better suited for CEA. With the recent, rapid development of genome sequencing and functional genomic analysis on many vegetable crops, it is feasible to apply genome-editing technology to develop new vegetable and fruit cultivars for CEA production.

Critical needs and research:

- How can we screen USDA plant germplasm resources to identify and develop new plant materials suitable for CEA production systems (greenhouse and indoor vertical)?

- What opportunities exist to establish public labs dedicated to making gene-editing and modifications to develop new cultivars useful for CEA production?
- How can we utilize rapid plant breeding to develop new cultivars and rootstocks suitable for CEA production (e.g., high yield, good quality, early maturation, and continuing production)?

Table 15: Challenges, needs, and opportunities in the Genetics theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
USDA plant germplasm resources are valuable materials to screen under CEA conditions for specific traits (flavor, quality, yield, and pest resistance...) that are important for growers and consumers.	3.78	0.27	26
Develop labs dedicated to making gene modifications for greenhouse and related crops. Gene-editing technology could be useful to accelerate the breeding process for new cultivar development suitable for CEA production systems (greenhouse, vertical farming).	3.52	0.26	26
Controlled ecosystems that mimic field conditions to test phenotypes of bioengineered plants, beneficial microbial inoculants developed in the lab, and provide platforms for rapid development of microbiomes beneficial for plant and environment to reduce the operational costs and to make CEA practical in diverse environments (urban and remote, climate variations, etc.).	3.52	0.30	27
Develop resistant rootstocks and scions against emerging diseases, especially for challenging new viruses, etc.	3.43	0.30	23

Table 16: Research questions in the Genetics theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
How to best work with stakeholders to identify traits that need improvement in greenhouse or vertical farming crops and then identify the underlying genes in available genomes (lettuce, spinach, tomatoes, etc.) - then using gene-editing to manipulate these preferred traits (disease resistance, growth profile) without adversely influence other characteristics (flavor, nutritional content, and biochemical compounds).	4.50	0.18	16
How best to develop means to evaluate existing germplasm for CEA suitability (greenhouse and vertical agriculture) - accelerate the breeding process through speed breeding to develop new cultivars that are suitable for CEA production systems (greenhouse and vertical farming).	4.46	0.19	13
How to communicate and educate the public to increase popular acceptance of genetically modified crops so that genetic innovations for better CEA are not a liability to the industry?	4.27	0.17	15

SYSTEM INTEGRATION AND RESILIENCE

Discussion summary

CEA systems depend on and must be well integrated into the broader economy and infrastructure system to be successful. Integration issues related to energy supply and management, including CHP; land use and planning; building design; transportation and distribution systems, including the cold chain; and water and waste management services were mentioned in the workshop. One example of a specific integration challenge was highlighted in the discussion of DC microgrids. Though applying DC microgrids in CEA would provide clear energy benefits, there is an associated "chicken-and-egg" problem. When DC loads are insufficient, installers will not create a microgrid; when there are no DC microgrids, manufacturers will not produce DC loads. This example highlights how system integration creates a complex set of both risks and opportunities for the successful expansion of CEA in the future that must be explored in a comprehensive research portfolio.

Poorly integrated systems can contain weak connections between interdependent systems at risk of cascading failures, including the CEA facilities themselves. We have seen this as the COVID-19 pandemic has highlighted vulnerabilities in food production and distribution systems that led to shortages and supply chain disruptions. CEA can be strategically deployed to improve resilience. For example, integrating renewable generation can promote energy efficiency but also support resilience. CEA shortens supply chains and gives people the opportunity to interact more directly with the food system, potentially enhancing social cohesion and resilience. Deploying CEA to reduce access issues in food deserts addresses social sustainability concerns even as they improve the security of the food system overall.

Research is needed to ensure that CEA can be integrated with both existing and potential future infrastructure systems, many of which are evolving significantly, without negatively impacting resilience. CEA systems can be strategically sited near reliable transportation or needed resources to simplify integration and provide resilience. Smaller, more distributed systems may be easier to integrate than larger ones in areas with limited available land, particularly in urban areas. We need to better understand economies of scale in CEA to avoid excessive costs in these smaller deployments. Further, we need to explore how to provide resilience without incurring unnecessary redundancies that increase costs, energy use, and/or resource and environmental implications. The long-term success of CEA requires that we evaluate these tradeoffs to make informed design decisions that balance risks.

Like in many other aspects of CEA, one important limitation for integration and resilience is a lack of sufficient high-quality data to characterize the problem. Attendees noted the need for committed industry partners willing to share detailed data to support improvements to, and the expansion of, CEA. In many existing CEA facilities, data is tightly protected to maintain competitive advantages. Efforts to anonymize data for this research will be valuable.

Critical needs and research:

- In what ways does CEA increase or decrease the resiliency of our food supply system? Can models be developed to estimate resiliency while accounting for predicted scarcity of resources and climate change?
- What are the best technology integration strategies (which technology, how, for which context) for designing efficient, resilient, and sustainable CEA facilities? Can the design process be improved to address tradeoffs for integrating different technologies?

Table 17: Challenges, needs, and opportunities in the System Integration and Resilience theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
New technologies to utilize natural solar light (transparent roof, solar collectors, moving benches/tracks) to supplement energy intensive artificial lighting are needed.	3.97	0.27	26
The data needed to answer resilience (and other) CEA research questions are going to be hard to gather. Committed industry partners (usually very unwilling to share publicly) are needed to conduct meaningful research.	3.71	0.26	26
Energy storage for use when renewables are not producing/off peak hours is not currently accessible for CEA.	3.55	0.30	27
There are opportunities to develop better approaches to integrate plant and animal (including fish) production systems in CEA as well as to integrate multiple components of CEA to create a sustainable close loop (e.g., use plant material for biofuels, enhance nutrient content with in-situ fermentations).	3.54	0.30	23
Resilience requires better methods for assessing risk and providing redundancy. Risks associated with failing supply chains and food security shocks can completely change the assessment of the costs and benefits of CEA, especially in urban applications. There is also an opportunity within CEA to redefine redundancy not as "bigger" but as "multiples" and preferably as modular multiples.	3.52	0.34	24
There are many variables to optimize for energy use and plant productivity efficiency. A holistic rapid iteration set of assays that act as proxies for final production are needed so that these factors can be more easily tuned.	3.46	0.32	26
Better understanding of the tradeoffs associated with siting CEA facilities near existing industries for energy and other benefits is needed. Accessing those benefits has costs; benefits could be negated if the partner facility closes.	3.43	0.31	26

Table 18: Research questions in the System Integration and Resilience theme. Ratings for importance are on a scale of 1-5 where highest importance is 5.

Topic	Average rating	Standard deviation	Ratings (#)
In what ways does CEA affect the resiliency of our food supply system? Can models estimate resiliency and account for future uncertainties (scarcity of resources and climate change)?	4.29	0.17	21
What are the best technology integration strategies (which technology, how, for which context) for designing efficient, resilient, and sustainable CEAs? Can the design process be improved to address tradeoffs for integrating different technologies?	4.20	0.26	20
What strategies will enable successful data sharing, including negative impact data or complex tradeoffs (e.g., a CEA setting can improve productivity and disease control but result in shorter shelf life)?	3.75	0.26	20
How can NASA's focus on food requiring intense resource efficiency in a hostile environment be leveraged toward the same needs in CEA on the ground?	3.71	0.32	21
Can "pop-up" CEAs be created to exploit low-cost opportunities?	3.39	0.31	18
Can a resilient system operate without a food preservation component?	3.25	0.32	16
Can integrating plants and animals in a closed CEA system improve profitability?	3.00	0.29	18
Can experiments be designed to determine how plants perform in a partial-gravity space environment (e.g., lunar or Mars gravity), both from a fundamental biological research perspective as well as practical perspective to determine if it is possible to grow enough to feed people?	2.89	0.29	18

Envisioning the Future of CEA

As part of the workshop, participants spent an hour getting to know each other in a series of three different randomly assigned breakout groups. Each breakout session had a different guiding question. These questions were:

- What brought you here today?
- What excites or intrigues you about collaborative research related to CEA?
- What do you think controlled environment agriculture could look like in 5 years if collaborative research between ARS, DOE, NASA, and others is successful?

These questions were intended to facilitate networking opportunities in the virtual setting while also inspiring participants about the potential of research into more efficient CEA implementation. Participant responses to these questions were voluntarily documented in XLEAP.

The answers to the third question, "What do you think controlled environment agriculture could look like in 5 years if collaborative research between ARS, DOE, NASA, and others is successful?", helped define a vision for a future where a research agenda similar to what is presented in this report is successful. Below we present selected responses that exemplify the possible transformation of CEA if a research collaboration involving ARS, DOE, NASA, academia, and industry is successful. Note that these answers were given while we were still brainstorming topics that should be considered and, therefore, are not directly tied to the research questions we have outlined. Regardless, they capture the scope of transformation envisioned by workshop participants. Responses have been organized post facto by primary research theme(s). Some research themes identified in the workshop are not represented. Appendix C contains all XLEAP responses.

Microbiome and Genetics

- [We will have] developed microbial amendments (probiotics) in the water that suppress pathogens, increase biomass, and improve nutritional content of CEA crops.
- [We will have successfully developed] plant beneficial microbiomes that impact food flavor, quality, affordability under Climate Change conditions by using fabricated ecosystems that mimic field/natural conditions (soil types, climate, water).
- [We will have adapted] a greater diversity of crops will enter vertical production systems.
- Research [will achieve] breakthrough understanding of how to manipulate everything about the grow environment, from the microbiome to what allows maximum nutrient uptake, to achieve truly customized food offerings. **Success looks like research and food system partnerships that achieve exponential improvements in food together.**

Energy Efficiency

- [The] energy footprint for CEA will be $^{1}/_{3}$ of today; waste heat in farms will be seen as an opportunity vs. a problem.
- We need a major leap forward in energy production and/or energy efficiency to fully embrace controlled environment agriculture (vertical farms). Small gains in energy efficiency will not be sufficient to grow plants in warehouses.
- Greenhouses will use electrochromic and/or other type of dynamic glazing to continuously optimize light and heat transfer. The delivery of daylight and electric lighting to the appropriate locations in the plants will be optimized to minimize losses.
- [We could achieve] light-free photosynthesis in a closed self-sustaining system.

Water and waste management

- [We will maintain] year-round growth in small footprint vertical growth chambers with recycled water and minimal inputs.

Social and Environmental Sustainability

- [We could] deploy technical assistance/workforce to implement blueprints and innovations in our communities *with* our communities (emphasis added).
- [We could achieve] sustainable production of sufficient, affordable, and healthy food for people and animals with responsiveness to environmental and resource challenges.
- US being self-sufficient and not importing food anymore — maybe even exporting to other countries in an energy- and water-efficient way.

System Integration and Resilience

- We will have learned how to manage energy needs through renewables, integration with waste heat, etc. so that CEA can provide critical supply chain, climate resilience and food access to those who do not currently have it.
- Climate change and economic conditions require a holistic consideration of both the physical infrastructure that is resilient and cost-effective in the long term (considering the life-cycle costs).

General

- Technology advances from several bins (renewable electricity generation and storage, building envelope design, transactive energy and forecasting, automation, and control) will come together and be integrated to transform CEA. [It] will become the default approach, with huge energy and cost savings, with benefits of strengthening communities, resilience, and avoided pollution.
- US leading research and development space for CEA systems, not lagging behind Japan or the Netherlands.

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