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WORKSHOP REPORT

RESEARCH AND DEVELOPMENT POTENTIALS IN INDOOR AGRICULTURE AND SUSTAINABLE URBAN ECOSYSTEMS

U.S. Department of Agriculture, Office of the Chief Scientist & U.S. Department of Energy, Bioenergy Technologies Office | Washington D.C.

United States Department of Agriculture | Research, Education & Economics | Office of the Chief Scientist

LETTER FROM THE ACTING USDA CHIEF SCIENTIST

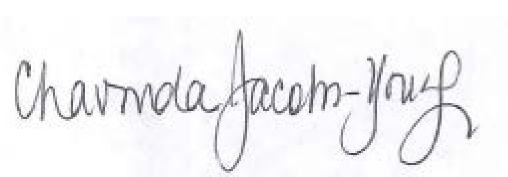
Dear Colleagues,

I am pleased to forward this report "Research and Development Potentials in Indoor Agriculture and Sustainable Urban Ecosystems." It summarizes findings from the joint U.S. Department of Agriculture and U.S. Department of Energy workshop held in Washington D.C., June 27-28, 2018.

USDA strives to, in the words of Secretary Sonny Perdue, "Do right and feed everyone." Meeting this goal while addressing global challenges at the food-energy-water nexus will require interdisciplinary innovation on a grand scale. Indoor agriculture and industrial urban ecosystems represent two strategies among many that could be deployed simultaneously.

This report represents the first step in an ongoing process of identifying and characterizing Research and Development (R&D) needs and opportunities in this nascent field, and determining its long-term sustainability and scalability. Robust interdisciplinary and interagency collaboration will remain vital as we continue these conversations and explorations.

Sincerely,



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EXECUTIVE SUMMARY

On June 27 and 28, 2018 the U.S. Departments of Agriculture and Energy co-hosted a workshop in Washington, D.C. The workshop engaged stakeholders, experts, and researchers from across the United States in interdisciplinary discussions on the potential for indoor agriculture (IA), in the context of sustainable urban ecosystems, to address global environmental challenges. Participants collaborated to identify Research and Development (R&D) challenges, opportunities, and needs relating to six major areas:

1. Community Services
2. Economics
3. Ecosystem Services
4. Plant Breeding
5. Pest Management
6. Systems Engineering

Discussions relating to each of these six major themes are summarized in the body of this report.

GLOBAL CHALLENGES AND INNOVATIVE SOLUTIONS

Developing sustainable strategies to feed our growing and increasingly urban global population requires vision, interdisciplinary cooperation, and innovation on a grand scale. Indoor agriculture, a specialized form of Controlled Environment Agriculture, represents an emergent and rapidly growing field with potential to reduce many of the environmental and social challenges facing food, energy, and water. By 2050, we will need almost 70 percent more food, 30 percent more water, and over 50 percent more energy production. [1] Climate change is impacting crop yields and creating unpredictable agricultural growing conditions, and the land currently dedicated to agricultural production is insufficient to meet increasing global food demand. The Food and Agriculture Organization of the United Nations (FAO) estimates that, today, one in nine people does not have enough food, a disparity that is only projected to grow in the future. [2]

[1] Hoff, H. 2011. Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm, Sweden: Stockholm Environment Institute (SEI).

[2] Food and Agriculture Organization, International Fund for Agricultural Development, United Nations International Children's Emergency Fund, World Food Programme and World Health Organization. 2018. The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition. Rome, FAO.

IA operations, which often grow produce on multiple levels using artificial lighting, can provide solutions to many of these issues because they are protected from unpredictably variable climates, can be constructed in even the most extreme environments, and use substantially less water than traditional growing operations. When integrated into multi-storied structures, IA systems create more growing space vertically to increase the scale of production, thereby addressing growing issues of scarce farmland.

In urban contexts, IA operations can integrate into industrial ecosystems that promote circular water and energy systems. Food production within urban ecosystems can reduce food transportation distances, providing urban communities with fresher and more nutritious produce. And, agriculture within urban systems can further benefit communities by providing new job markets and re-purposing industrial structures. [3] [4] [5]

SUMMARY FINDINGS

The main conclusion from workshop participants is that the fast-growing and interdisciplinary field of IA, especially in urban contexts, holds enormous potential for addressing the global challenges in food, energy, and water, as well as the needs of a growing population. Detailed findings from the six major R&D themes discussed can be found in the body of this report.

Participants also agreed that to meet the goal of growing the IA industry sustainably and effectively, continuing conversations are needed to:

- Develop cross-disciplinary research and training priorities;
- Formulate a set of industry best practices; and
- Expand indoor agriculture-specific knowledge and industry standards for economics; plant breeding; integrated pest management; food safety and nutrition; engineering; and innovative circular waste and water systems.

[3] Aerofarms, 2018, https://aerofarms.com/
[4] Plenty, 2018, https://www.plenty.ag/sf/
[5] Despommier, D. 2013. Farming up the city: the rise of urban vertical farms. Trends in Biotechnology. 31(7)388-389.

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RESEARCH AND DEVELOPMENT POTENTIALS IN INDOOR AGRICULTURE AND SUSTAINABLE URBAN ECOSYSTEMS

COMMUNITY SERVICES

Urban communities often represent patchwork composites of socioeconomic disparities and opportunities, many of which are reflected in the availability and affordability of fresh produce and other food goods. Indoor agriculture (IA) in urban and near-urban areas has the potential to act as a consistent, local, and accessible producer and distributor of fresh produce. If these farms are placed strategically, this possibility of local food production, processing, and distribution could be especially impactful for urban areas without reliable access to affordable and fresh produce. Such farms could also have far-reaching impacts in traditionally underserved communities by creating opportunities for training employment and business development in an emerging sector.

THE DISCUSSION

The potential services resulting from the implementation and scaling of indoor agriculture extend to surrounding communities, in terms of both produce availability for underserved populations, and the creation of technically skilled jobs. The impacts of these potentialities, accessible fresh produce and job creation, means that strategically placed and developed farming operations could support improved public health and green infrastructure (especially water management), thereby reducing the costs associated with negative social and environmental externalities while increasing socioeconomic opportunity. Discussions in this session focused on strategies to promote economically viable IA, controlled environment agriculture (CEA) more broadly, and other small-scale urban farming operations in such a way that they simultaneously promote health, improve ecosystems services, and expand economic opportunities in communities and the urban scape in which they operate.

CHALLENGES

- Affordable and ecologically sustainable water availability for urban IA could be difficult due to municipal design; however, closed loop systems that capture and recycle water, and green infrastructure installations that utilize synergies between urban agriculture and storm water management, can offer viable solutions.
- Community buy-in of IA and local produce as a value-added system.
- A socially responsible business model that balances the dietary needs of underserved neighborhoods with the high revenue potential of high-end niche markets in the local foods sector of urban communities.
- Communication strategies promoting intentions to create jobs and include communities as members of a local food shed.
- Strategic plans to coordinate agricultural technologies with municipal economies, while carefully taking measures to include and develop a local workforce.
- Developing an urban-rural connectivity–a spatial analysis of potential production locations–and a technology transfer framework to promote job creation in agriculture in rural, peri-urban, and urban locations is lacking and needed.

NEEDS

- Investigation of potential benefits and opportunities for rural communities and industries that could result from the growth of specialty crop production in urban and near-urban areas.
- Strategies to implement CEA, IA and bio-intensive farming in urban areas in such a way that they create opportunities for training, job creation, business development, and improving quality of life and economic opportunity for urban and near-urban poverty.
- Modular and accessible series of tools, policies, and recommended methodologies for developing and implementing CEA and IA operations in urban settings.
- Analysis of the socio-economic repercussions of scaled CEA and IA, especially in terms of how these industries impact local property values.
- Analysis of scalable IA and small-scale bio-intensive models of agriculture and viable investment strategies and funding mechanisms in resource-poor urban communities.
- Study of the impacts of urban IA on food-shed size, produce accessibility and price, and resulting impacts on public and community health and ecosystems services.

OPPORTUNITIES

- Training, education and employment opportunities in underserved urban communities, with a special focus on reducing prison recidivism rates.

might lower health insurance costs.

- Co-development of circular industrial ecological systems, for instance self-sustaining micro-energy grids centered around IA operations.
- Minimize community disruption and to incorporate urban planning and large-scale urban recycling in post-industrial cities by converting neglected and abandoned buildings into productive and sustainable IA.
- Partnerships with the U.S. Department of Health and Human Services local employers, interested non-profits, and State and local governments to consider how increased access to fresh produce in underserved areas might lower health insurance costs.

ECONOMICS

IA leverages techniques in horticulture and engineering to optimize crop quality and systems efficiency to allow crop production year round. IA and CEA systems more broadly are experiencing increased attention for their potential environmental and social benefits, and because many consumers today increasingly demand fresh, local, high-quality produce. [6] However, many economic questions remain regarding the scalability and long-term sustainability of these systems. While CEA–from high-tunnel systems to indoor vertical agriculture–has the potential to supply large quantities of high-quality produce, fully indoor systems, IA, also require high capital investment and energy operating costs. Their successful operation additionally requires interdisciplinary coordination and expertise in business, horticulture, and engineering.

THE DISCUSSION

The economics small-group discussions focused on how we can accelerate and scale innovation in indoor food production in urban and near-urban areas to be an industry leader in the global market. Discussions also covered the importance of taking existing infrastructures into account in water, energy, transportation and research. Equally important were the considerations of generating productivity; environmental health; promoting rural prosperity; resilience; and job creation and economic benefits.

[6] Low, S. et al. Trends in U.S. Local and Regional Food Systems: A Report to Congress. 2015. A Report Summary from the U.S. Department of Agriculture, Economic Research Service.

CHALLENGES

- Heating, ventilation, and air conditioning energy transfer issues in IA systems are rampant and oftentimes not transparent.
- Many moving parts could complicate the industry. Stakeholder needs include consumers, consistent buyers, acceptable prices, wholesale buyers and quality products.
- Determining the potential opportunities and challenges created for rural agricultural production in an economy that features widespread urban farming.
- IA/CEA often requires a highly skilled technical workforce. Characterizing job transitions and reconciling this trend with our current agricultural economy will be crucial.
- IA typically has high startup costs, and investments and returns must be considered in terms of business goals, crop choice, products, markets, customer needs, and location.

NEEDS

- Analysis of scale as it relates to the viability of individual production enterprises and the industry more broadly.
- Knowledge-sharing, or shared-value creation framework, of a national vertical-controlled agriculture industry and ramifications for cities, neighborhoods, and public health and wellness.
- Identifying consumer needs and preferences is key to determining pricing relative to field-grown crops.
- Economic analysis of how and when startups can thrive in this field as there has already been entrepreneurial innovation in this space.

OPPORTUNITIES

- A reduced carbon footprint and the development of a circular economic value system. With this opportunity, monitoring the means and results of production is important in terms of seed source, fertilizer use, waste stream utilization, and energy and water consumption will be important for potential feedstock and logistics and conversion topics.
- Public perception and marketability of IA, i.e., can producers market the natural resources that have been "saved?"
- Industry and stakeholder partnerships to drive down startup and capital costs.
- As the cost of technology and production decreases, IA/CEA operations can also aim to create shared value for underserved urban and near-urban communities through job creation and by offering local, fresh, and nutritious produce.
- Improve urban resilience and revitalization through job creation, access to more affordable and secure local food in cities, and the development of circular local economies.

ECOSYSTEM SERVICES

IA/CEA operations represent artificial ecosystems designed to deliver food products to human populations. Ecosystems are much more complex and involve diverse species that interact to deliver four classes of services that benefit humans as well as other species:

1. Supporting services (provide habitats for plants or animals and maintaining a diversity of species),

2. Regulating services (control ecosystem processes that create acceptable conditions for life as we know it),

3. Provisioning services (supply materials, energy and products), and

4. Cultural services (supply non-material benefits).

How might we design IA systems to mimic ecosystems that are diverse, resilient, and deliver multiple benefits to humans and other species?

THE DISCUSSION

The group first explored research questions related to how IA delivers the four classes of ecosystem services. The group examined what sustainability implies for IA and discussed whether such systems can ever be sustainable if they constantly require resource inputs from the external environment. Key themes in the discussion focused on diversity of crops, growth media/methods and benefits for IA/CEA to be considered sustainable and resilient.

CHALLENGES

• Managing the resource requirements (particularly energy) for IA/CEA. This includes understanding the resource needs for different systems (e.g. hydroponic versus aeroponic) and considering geographic contexts (e.g. water/energy resource availability).
• Based on appropriate scenarios and assumptions for large-scale adoption of IA/CEA systems, what are the potential land-sparing and associated environmental implications?
• Co-developing plant breeding/modifications and environmental controls in order to deliver higher nutritional value food while reducing resource requirements.
• Making room for small growers in urban environments. An industry association might help with training, but only if there is room for the small grower, too.
• Accounting for cultural services and (non-material) benefits. Can we develop methods to evaluate and incorporate the value of these services?
• Is there demand and space for organic and genetically engineered foods in IA? How can we assess their acceptability to different market segments?

NEEDS

• Workforce development is necessary for industry growth; however, there is a need to balance supply and demand of personnel. Basic training would encompass food safety and technology/managing automation.
• Equity in IA/CEA. New policies, programs, and strategies to identify and encourage small, community-based entrepreneurs and organizations to participate in production so that the benefits reach communities that have been traditionally disadvantaged. For example, Aerofarm's site location, hiring and outreach strategies suggest ways that for-profit vertical farms can have significant impacts on low-income, minority, and food desert communities.
• Integrated technoeconomic and life-cycle assessments to identify the most profitable and environmentally impactful crops under various scale and system configuration scenarios.
• Creating diverse ecosystems that deliver multiple benefits in addition to food, such as water and air purification.
• Rules and guidelines need to be developed to establish standards and best practices for growers at all scales. These would include health and safety, quality controls, and energy use guidelines.

OPPORTUNITIES

• Formation of an industry alliance/association help to share best practices, information about costs/technology/crop systems/food safety, encourage certification, and could help small producers adopt best practices.
• Identifying and quantifying the ecosystem services of IA/CEA and decentralized agriculture could help to influence policy and increase incentives.
• Non-commercial growing: Indoor "victory gardens" or indoor community growing spaces could provide additional ecosystem services, particularly community building and cultural services.
• Economic analysis of local circular systems (with multiple actors and functions), especially for decentralized agriculture and energy production.

PEST MANAGEMENT

A controlled environment allows crop production year-round in regions where they would otherwise be impossible. However, a fully indoor growing system– regardless of building design and sterile protocol– will not be free of insect pests and diseases. Due to the monoculture and intensive production practice under IA/CEA, a major outbreak of a disease or a pest could seriously affect the business operation. Common insect pests identified by IA/CEA growers include: aphid, thrips, whiteflies, and spider mites. Major diseases are powdery mildew, Pythium root rot, viruses and viroids. Typically, seed-borne and mechanically transmitted diseases are more prevalent. R&D can help to develop protocols and specific strategies for the rapid detection and management of specific pests.

THE DISCUSSION

Pest management discussions focused on crop insects, and diseases in a spectrum of CEA environments including IA, greenhouses, and high and low tunnel systems. Discussions also covered the importance of training, personnel, sterile protocols, and targeted pest management strategies that take into account beneficial insects, such as predators, parasitoids, and pollinators.

CHALLENGES

- Knowledge gaps and best practices: There is a general lack of awareness among growers that pest prevention measures should be implemented even before insect pest and disease outbreaks have occurred.
- Currently, there are limited funding sources for CEA agriculture R&D due, in part, to the interdisciplinary and nascent nature of the field.
- There is a dearth of CEA-specific pest and disease control options. Many management and prevention strategies from field agriculture do not translate to CEA. Identifying these gaps and developing research programs for CEA-specific management practices will be important. This is also true for CEA-specific monitoring, scouting, and prediction of pests and diseases, as well as recommendation of best management options.
- A lack of strong modes of interdisciplinary communication can result in many CEA systems being designed to meet energy and lighting needs without accounting for the biological aspects of the systems as they relate to crop biology and pest management.

- Promoting research and developing robust networks for innovations and strategies that will enable ecofriendly/sustainable pest management under controlled environment compatible with pollinator health.
- Research on the adaptation and implementation of existing field technologies for controlled environments.
- Developing strategies for managing and interpreting data generated from controlled environments.
- Development of funding programs focused on controlled environment agriculture and associated “minor” crops that cannot generally compete with other field crops. These funding programs would be most effective when researchers are connected with stakeholders to ensure that research results have direct applications.

NEEDS

- Promoting cross-disciplinary education, communication, and workforce development programs is an urgent need to promote function, effective data analytics, and efficiency in this interdisciplinary field. For instance, engineers and technicians should be able to understand pest management needs when designing CEA structures.
- Building networks and collaborations between researchers and industry stakeholders to enable development and implementation of cutting edge, user-friendly technology and strategies.

OPPORTUNITIES

- Due to the engineered and predictable nature of some CEA systems, there is potential to expand on biological control methodologies in CEA that are not possible under field conditions.
- Technologies already implemented in Europe and other countries for CEA could be considered and adapted for local use.
- Because CEA is a nascent field, there is great opportunity for the development of transdisciplinary approaches for pest and disease management including harnessing the power of big data in these systems.
- The development of affordable technologies that growers can use for decision making, such as simple, rapid, accurate, economical, easy-to-use tools for pests and disease detection under controlled environment conditions.

PLANT BREEDING AND INNOVATION

Plant breeding for IA/CEA has the potential to develop a greater diversity of vegetables that are commercially viable beyond crops that are available for the industry today. The goals of many breeding programs supporting traditional land-based production systems are primarily focused on yield, transportability, and pest resistance. In IA systems, a large focus for breeding programs will be optimal adaption of those key traits to controlled and intensified production environments. However, with IA production comes the potential for reduced pests and shorter transportation distances, meaning that breeding programs have the opportunity to prioritize additional and often overlooked traits to benefit both production systems and consumers. Other breeding goals would involve the coupling of production with introduced technological innovations such as genetically optimized production under supplemented light, temperature, and nutrient conditions.

THE DISCUSSION

Participants began to evaluate the types of crops that are best suited for IA operations and more intensively controlled CEA, along with their key traits and characteristics. Because of their high retail value, commercial IA production in the United States has largely focused on leafy greens, herbs, and other leafy vegetative stage fresh market produce. Future plant breeding programs that incorporate both traditional and advanced techniques should be expanded to consider production of non-leafy produce.

CHALLENGES

• Economically viable crop and species selection. In many instances, choosing a crop for a breeding program will depend on the market. Breeders should give thought to whether a crop is suited to novel production environments, or desired in nearby markets.
• Plant breeding is a long-term effort, and IA entrepreneurs are burdened by extreme risk, needing quick results to stay in business.
• Variety selection for IA breeding will depend on our ability to rapidly and reliably identify traits of interest through the refinement and diversification of high-throughput and non-invasive phenotyping techniques.
• Improved understanding of Genotype by Environment (GxE) interactions will be key to long-term success. GxE effects will fluctuate among crops, varieties, and growing conditions. Successful breeding programs should begin with candidate crops with robust germplasm collections; documented/ongoing breeding programs in greenhouse (preferred) or outdoor environments; genetic information; and metabolite profiling.
• Identifying focal traits for breeding programs. Focal traits might include: fast and complete seed germination, fast life cycle, dwarf or compact plant architecture, complete self-pollination, resistance to CEA pests, flavor, high water content, high harvest index, and increased nutritional content.

NEEDS

• A systematic evaluation of crop types and elite germplasm for both field and protected environment production should be conducted to determine candidates for new indoor IA breeding programs and compared with new genetic materials that are already selected for protected environments.
• Attention to shelf life (e.g., quick-wilting leaves), packaging and processing considerations (e.g., leaves that cling together), and plant fragility (e.g. brittle leaves and petioles)
• Address physiological disorders that could impact IA production, such as tip burn in lettuce.
• It is recognized that other countries such as the Netherlands, Taiwan, and Japan may be more advanced in their knowledge and practice of CEA/IA production. An assessment of the current state of the practice will be foundational to developing a U.S. approach.
• Consider the roles of private-public research partnerships that complement investment to accelerate progress in the commercial establishment of IA enterprises.

OPPORTUNITIES

- Using stable, controlled environments, it is possible to substantially increase plant productivity per unit area far beyond what can be achieved in conventional agriculture.
- Crops bred for CEA inputs such as optimized light spectra, water, nutrients, and other inputs that are normally limited or only periodically available in field conditions.
- Crops with traits that do not receive primary attention in traditional breeding programs, such as increased nutritional content and improved flavor.
- Advanced breeding methodologies. There is great potential for the use of gene editing and other advanced methods to target specific traits and speed up selection.
- Breeding programs can build upon National Aeronautics and Space Administration's agriculture research, and reconfigure previous work for earth-based systems.
- The potentially conflicting time frames of breeding and entrepreneurship create space for diverse partnerships in the public, private, and academic sectors with robust technology transfer and licensing agreements.
- Breeding partnerships to enhance growth optimization, develop research facilities, and identify novel goals and traits that meet both consumer and producer needs. There is additionally space to coordinate with ongoing research at agricultural universities on controlled environment agriculture above and beyond greenhouses and growth chambers.

SYSTEMS ENGINEERING

IA combines interdisciplinary knowledge and technical expertise in horticulture and engineering to develop controlled spaces for year-round optimized crop production, quality, and efficiency in a range of climates. Advances in system architecture, engineering, automation, nutrient cycling, data analytics, crop genetics, lighting efficiency, and system design are necessary to make these systems efficient, safe, cost effective, and productive at large scales.

THE DISCUSSION

Systems Engineering discussion focused on the elements of systems design, cost reduction, and efficiency when constructing a vertical or IA system. IA presents certain design constraints and challenges to ensure efficient production and healthy crops. These considerations include lighting, waste water management, nutrient cycling, energy supply and use, air flow, carbon dioxide regulation, and automation. Opportunities exist to expand the understanding of both the science and practice of IA, and how new, more efficient technologies can be applied to reduce operating costs and increase productivity.

CHALLENGES

- Energy needs for IA are significant, leading to high operating costs; this makes investment in, and deployment of, efficient production system architecture a priority.
- The engineering of clean and safe production environments and harvest protocols are key to addressing food safety concerns.
- Challenges to scalability and success include high startup costs, required technical understanding, and optimized system architecture.
- Strategies for the sustainable management and analysis of waste.

NEEDS

- Holistic energy balance equation starting with electrical energy into the facility and ending with biomass energy out.
- Design and engineering advancements in climate control systems (for heating, cooling, and humidity control) and lighting to increase efficiency and reduce operating costs.
- Improved understanding of irrigation systems and systems engineering innovations in water-use efficiency and regulation, such as hydroponics, aquaponics, and aeroponics.
- Developing a transdisciplinary and integrative modeling framework that outlines the interactions of factors such as cost, yield, quality, food safety, and efficiency on production, scalability, and sustainability.
- Integration of system energy balance with both technoeconomic and life-cycle assessments to identify normalized costs for engineering system optimization strategies.
- Research, modeling, and data analytics to facilitate improved understanding of ideal growing conditions and crop tolerances, co-optimization of the production environment, and reduced energy costs through increased efficiency.

OPPORTUNITIES

- General operations cost model for IA. This model would consider all first cost and operational costs along with, on a crop-by-crop basis, growth cycles, packaging costs, and sales prices.
- Develop an improved understanding of plant physiological responses to light. Lighting directly affects crop yield and quality and represents a major operating expense. An improved understanding of light-plant interactions will enable more effective use of light to achieve higher yields with less energy.
- Develop a larger plant growth model that enables co-optimization of all cardinal plant growth parameters that can be applied to different crops and cultivars.
- Climate and moisture control technologies with improved efficiency and effectiveness.
- Improve efficiency and reduce cost for horticultural lighting, including source efficiency, spectral effectiveness, and optical delivery efficiency.
- Improved, lower cost processes for food safety and packaging.
- Where production practices are common, facilitate information sharing and training of best practices; develop trans-disciplinary horticultural IA workforce curriculum.
- Labor savings processes and automation approaches to reduce production costs.

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