URBAN CROP PRODUCTION IN VERTICAL FARMS

Optimizing resource use such as for energy, water, nutrients, and CO_2 is essential for the long-term viability of vertical farm systems.

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This article series is from the Resource Management in Commercial Greenhouse Production Multistate Research Project.

Indoor vertical farming systems or plant factories use controlled environment agriculture (CEA) technologies to grow high-value horticultural crops year-round in pre-existing urban warehouses or shipping containers. The internal building of warehouses is most often converted into a growing environment with the goal of achieving higher biomass production compared to outdoor or greenhouse production. The essential components of a vertical farm include multi-layer production shelves, hydroponic, aeroponic, or aquaponic growing systems and sole-source electrical lighting consisting primarily of high-intensity light-emitting diodes (LEDs) (**Figs. 1A and B**) or fluorescent lamps. However, detailed engineering design fundamentals for heating, ventilation, and air conditioning (HVAC) systems, uniformity of the environment, optimal delivery of carbon dioxide (CO_2), shelf spacing, smart lighting and shelf designs, and interaction of crops and surrounding climate in terms of heat and mass-transfer processes are often overlooked in such retrofits. Optimizing the use of resources such as energy, water, nutrients and CO_2 is essential for the long-term viability of vertical farm systems, where energy intensive lighting and HVAC systems can account for close to one third of the overall operational costs. The operational costs and resource use efficiency (defined as the ratio of resource fixed by the produce to resource used by the plant; Kozai, 2013) of multi-tier-based vertical farm systems can be improved by appropriate production system design modifications for key technologies and control strategies while considering the crop-specific minimum environmental requirements such as light intensity and quality, air temperature, velocity and flow pattern, CO_2 and uniformity of these variables.

Many millennial vertical farmers are data-driven and rely on recent technology developments in sensors, environmental monitoring and control, and information and communication technologies. Integrated monitoring

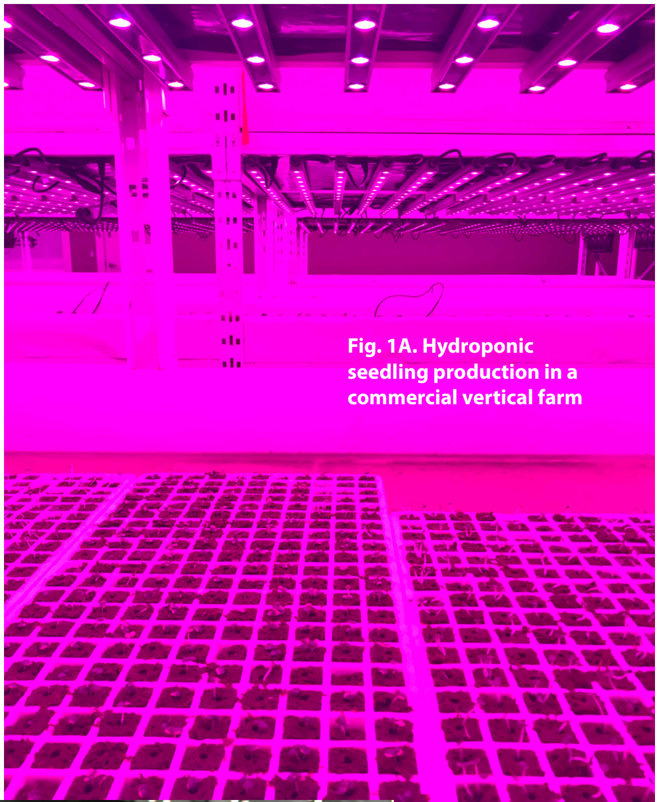
Fig. 1A. Hydroponic seedling production in a commercial vertical farm


Fig. 1B. Lettuce production at the University of Arizona Controlled Environment Agriculture Center Urban Agriculture Vertical Farm Research, Teaching and Outreach Facility

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and control of the crop and production system and analysis on average account for about 9 percent of a farm workforce's weekly labor hours (Agrilyst, 2017). It is expected that these technologies will further advance with integration of the diverse set of analytics platforms made available for growers and system operators empowering them to improve production quality and overall resource use efficiency. The technologies that vertical farming operations are most excited about include automation, HVAC, LED lighting systems, smart sensors and data analytics.

Challenges in vertical farming

Several economic challenges make vertical farming a difficult sector to enter and be profitable including both high start-up costs (particularly lighting, vertical growing systems, and sufficient HVAC capacity) and high operating costs (especially energy and labor). In greenhouses, labor is typically the largest production cost followed by energy. In vertical farms, energy costs may be equal to or greater than labor. In a recent survey of CEA operations, 27 percent of vertical farms reported being profitable as compared to 67 percent of greenhouses (Agrilyst, 2017).

In 2016, an energy use simulation was conducted for lettuce production in greenhouses and vertical farms in diverse climates across the U.S. Per unit of lettuce, vertical farms in Minneapolis would require 1.4 to 2.4 times more energy than greenhouse counterparts; while in an arid climate like Phoenix, a vertical farm would require five to 10 times more energy than greenhouses (Harbick and Albright, 2016). Energy use was evenly split between lighting and HVAC systems. Another simulation-based study (Graamans et al., 2018) compared greenhouses vs. vertical farms in the Netherlands, United Arab Emirates, and Sweden in terms of resource use efficiency per unit biomass of lettuce: In all cases, purchased energy (heating plus electricity) used by greenhouses was less than plant factories. Climate made a large difference in the extent of energy savings. In a moderate climate like the Netherlands, greenhouse energy was three times less than the plant factory, while in an extreme northern climate like Sweden, greenhouses used only 15 percent less energy than plant factories. However, beyond energy, it was noted that vertical farm-based production could achieve higher productivity for all other resources (water, CO$_2$, and land area). Currently, energy costs average $8 per square foot production space and represented 25 percent of annual production costs in large vertical farms (Agrilyst, 2017). Therefore, there is further need for research on analysis of resource use efficiencies and to develop resource-conserving environmental control strategies (**Fig. 2**).

Automation in vertical farming

While indoor production may lend itself to increased automation (vs. field production), the nature of vertical farming (multi-layered production) appears to make it difficult to automate. Processes that in 2-D greenhouses (moving plants to the production space, respacing, sorting, and harvesting) are more time-consuming and labor-intensive in 3-D.

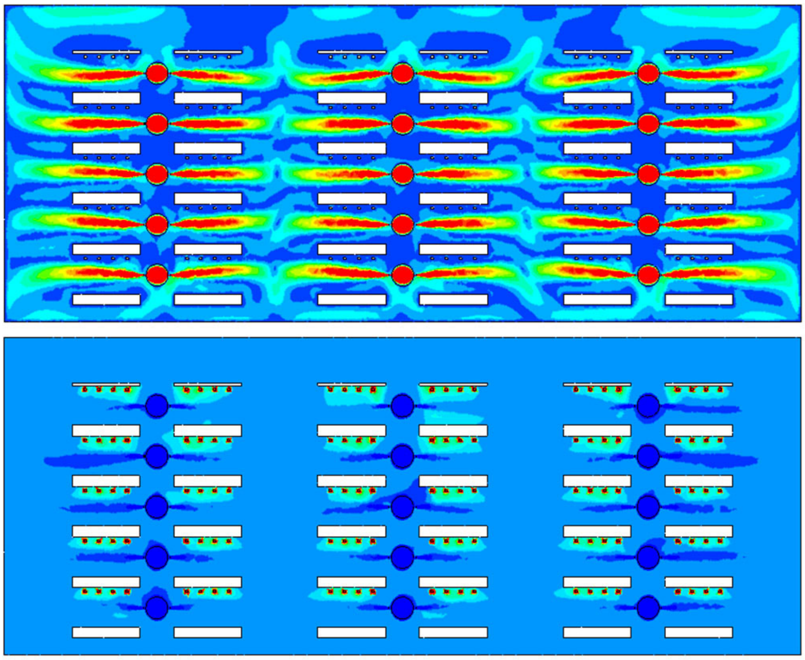

Fig. 2. Computer simulation analysis of climate (e.g. air velocity and temperature) uniformity in a vertical farm system

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Fig. 3. A scissors lift is used to access crops on upper levels in a commercial plant factory.

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For example, accessing crops for maintenance, monitoring, and pulling for harvesting typically requires added labor time through use of ladders or scissors lift in vertical farming (**Fig. 3**). Thus, automation and robotics systems need to be integrated for such operations.

Nutrient management in vertical farms

Indoor vertical farming operations take advantage of technology and automation to improve production efficiencies. This includes optimization of the root-zone (in terms of pH, fertilizer nutrients and dissolved oxygen) to produce high-quality crops and reduce nutrient waste. However, managing nutrients in vertical farming does not have to be high-tech or complicated. In addition, common nutrient management techniques used in greenhouse hydroponic and container crop production also apply to vertical farming.

Measuring electrical conductivity (EC) and pH in the rootzone are common methods for monitoring crop fertility. EC refers to the concentration of total nutrients surrounding roots, where greater EC values indicate a greater nutrient supply. pH refers to acidity or basicity in the root zone (where pH 7 is neutral), which influences the solubility and availability of nutrients for uptake. For most crops, nutrients are adequately available at pH 5.6 to 6.4. Multiple factors interact and can influence nutrients and pH during vertical farming production. For strategies on managing these factors, check out our previous *Produce Grower* article, “Edible crop species differ in their pH effect in hydroponics,” at **bit.ly/2CNsGUk**

In addition to measuring root-zone pH and nutrient levels, growers should periodically conduct detailed nutrient analyses on both the applied nutrient solution and plant tissue using a commercial lab. This helps growers check their own in-house pH and EC measurements, and verify that they are supplying individual nutrients in the correct amounts. Tissue nutrient analyses provide information on the amount of nutrients the plants are taking up, which helps growers adjust their fertilizer program for optimal plant growth and diagnose nutritional problems. Visual inspection of plants to diagnosis nutrient and other disorders remains important in plant factories but can be difficult under sole-source LED lighting. For example, under narrow waveband red and blue light, plant surfaces appear pink or purple. Some lights have a human vision feature to turn OFF red/blue light and turn ON white (broad-spectrum) light to inspect plants, or operators use special glasses with green lenses to see plants with natural colors. Computer vision systems can help enhancing plant inspection for growth, health monitoring and environmental control purposes and as an integral part of needed automation and robotics applications.

Future prospects

Vertical farming can meet consumer demand for high-quality, nutritious, chemical-free, and locally grown horticultural crops. Due to high production costs, there should be additional benefits delivered by sole-source lighting and CO_2 enrichment (such as phytochemical, nutrient or color enhancement). Research and development to improve labor and energy-use efficiency as well as increased uniformity of the growing environment will be important to address industry viability/profitability. Further, there is an increasing demand by the vertical farm industry for an educated/experienced workforce who understand both the biology and engineering of controlled environment crop production systems. Because the industry is young, the workforce has largely come from related industries without prior experience specifically in indoor climates. Therefore, it's critical to maintain and further grow controlled environment agriculture-based research, educational, and extension/outreach programs offered by higher education institutions to meet the industry's demands.

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Acknowledgements

*Financial support was received from the USDA National Institute of Food and Agriculture, Multistate Research Project NE-1335: Resource Management in Commercial Greenhouse Production. Murat is a professor at the University of Arizona (***mkacira@email.arizona.edu***), Ryan is an extension professor/specialist at the University of New Hampshire (***Ryan.Dickson@unh.edu***), Neil is an associate professor and extension specialist at Cornell University (***neil.mattson@cornell.edu***) and Roberto is an assistant professor and floriculture/controlled environment specialist at Michigan State University (***rglopez@msu.edu***).*