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Improving vertical farming efficiency through dynamic environmental control

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A Viewpoint on the Frontiers in Science Lead Article

Vertical farming goes dynamic: optimizing resource use efficiency, product quality, and energy costs

Key points

- The economic viability of vertical farming and related controlled environment agriculture is linked to crop productivity and operational costs, including electric power for lighting systems and heating, ventilation, and cooling.
- Reduced costs for electric lighting could be achieved by monitoring and actively controlling light intensity and photoperiods depending on changing power costs.
- Improved crop productivity could be achieved by selecting, breeding, and engineering crops specifically for vertical farming environments.

Dynamic control for plant growth environments

Controlled environments using vertically stacked hydroponic shelves were discussed as early as 1975 by agricultural engineers at the University of Connecticut in the United States (1). Today, the technology and industry have expanded rapidly around the world (2). Vertical farms can be located close to consumers in urban areas, thereby reducing shipping costs and losses from spoilage, providing consistent products throughout the year, and improving food security for areas lacking easy access to field agriculture (2). Interestingly, terrestrial vertical farming and agriculture for future space life support systems (e.g., on the Moon and Mars) have overlapping goals to be highly productive in a fixed volume and energy efficient, and both need to conserve and recycle water and nutrients (3). Indeed, National Aeronautics and Space Administration (NASA) research on controlled environment agriculture (CEA) was the first to use light-emitting diodes (LEDs) to grow plants; the first to demonstrate vertical farming with a wide range of crops at NASA's

Kennedy Space Centre; the first to demonstrate the production of root zone crops, such as potato, in recirculating hydronics, which is now used by many seed potato growers; and the first to monitor a wide range of volatile organic compounds in closed CEA settings, among more firsts (3). These innovations for space have enabled many of our current CEA systems on Earth.

By nature, controlled environments, such as vertical farms, offer the ability to manage temperature, humidity, carbon dioxide (CO_2), light intensity, photoperiod, and even spectral composition with current LEDs (2, 4). In the review of Kaiser et al. (5), the authors explore dynamic environmental controls in detail and use models to predict the effects on net photosynthesis and growth. These models are partially based on leaf gas exchange and ultimately need to be validated at the whole stand or canopy levels. They present data showing how commercial electric power costs can vary across the day and make a case for reducing lighting during periods of high cost and increasing it during periods of low cost. This uses the intrinsic flexibility of many plants to integrate variable lighting across the day (for example, think of field crops exposed to intermittent clouds and sun). Of course, this has limits but saving a few cents per megajoule of energy could have a profound effect on the economics of vertical farms. This concept was practiced in part nearly 50 years ago by a plant factory called Phytofarm in DeKalb, IL, United States (6). This facility produced leafy greens using the nutrient film technique and over a thousand 1000-W high-pressure sodium lamps (i.e., ~1 MW of electric power). By running their lamps at nighttime using "off-peak" power, they were able to save several cents per kilowatt-hour (kWh) from the utility company. With current LED technologies, lighting can be dimmed or ramped up very quickly to follow changing power costs, allowing even more flexibility for power savings across the entire day.

The authors address other factors such as temperature, nutrient solutions, and light spectral control that can be manipulated to optimize crop yields (2, 7), but this might be more challenging than dynamic lighting. For example, maintaining different temperatures for different crops or at different times of the day might require partitioned sections in the production area or modified air handling. The use of natural temperature gradients already existing in the vertical farm might be considered, such as the use of "cross gradient" research rooms at some phytotrons (8). Regardless, environmental testing with CEA crops is a vibrant area of research around the world, and the more we understand the response of crops to their environment, the more information will be available to growers. If dynamic control of the environment could provide even a modest 10–20% increase in productivity or similar decreases in operational costs, this could be important in the competitive CEA industry.

Designing crops for vertical farming systems

Based on the advances in crop breeding for field agriculture during the 20th century, similar selection, breeding, and genetic manipulations could improve controlled environment crops for vertical farms (9). Kaiser et al. (5) reviews some of these challenges and outlines the advantages they could bring. For example, vertical farms with stacked hydroponic systems need shorter growing crops to allow volume-efficient production. Breeding or designing crops with improved nutritional attributes or longer shelf life might make vertical farm produce more popular with retailers and consumers. If dynamic environmental control is used to manage lighting, having day-neutral crops or crops that are physiologically tolerant to continuous light could be beneficial. For example, many Solanaceous crops (e.g., tomato, pepper, potato) can be sensitive to long photoperiods, yet there are examples of genetic diversity for tolerance (10), suggesting breeding or engineering for tolerance to continuous light is possible. Physical attributes such as leaf color and shape, or different surface texture characteristics could be selected to appeal to consumers, and possibly help manage food safety challenges. Many of these same attributes have been and still are targeted for future space crops as well.

Concluding thoughts

Despite advances in vertical farming and the CEA industry over the past few decades, including the remarkable improvement in LED technologies (4), the survival of these businesses will depend on their economic viability and their ability to make a profit. Through targeted crop breeding/development for controlled environments and identifying environmental manipulations that could reduce costs without sacrificing productivity, there is potential to reduce vertical farm operational costs. This in turn would require advancements in environmental sensing and control technologies, perhaps including direct measurement of photosynthetic responses of the crops. The team of authors for this review is diverse, with many being well-accomplished in the field of crop physiology and CEA. They review a wide range of environmental management options and support their concepts with a thorough literature review. Their concept of dynamic control is visionary, and although it might not provide all the solutions, it has the potential to inspire innovative ideas on the topic. This could be pivotal for the future of vertical farming and CEA as a whole.

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Author contributions

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