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Vertical farming: a toolbox for securing vegetable yield for the food of the future

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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

- Moving to sustainable crop production via vertical farming could help limit the negative effects of modern agriculture on biodiversity and the global climate.
- Vertical farming systems (VFS) could play a crucial role in addressing the challenges associated with urban population growth by ensuring a more reliable and resilient supply of fresh vegetables, even in the face of catastrophic events like pandemics and extreme weather.
- The future success of VFS depends on achieving dynamic environmental control through the integration of sensors, machine learning, and nanotechnology, thereby significantly reducing the current limitations of these sustainable production systems.

Introduction

Agriculture has long been a part of human history, but the negative impact of modern agriculture on the environment is undeniable, leading to air and water pollution, soil, water, and mineral depletion, and decreases in biodiversity. The agricultural sector alone contributes around one-third of the 54 billion tons of greenhouse gases emitted by humans (1, 2). Considering such staggering numbers, the agriculture and food sector is called upon to implement urgent and necessary changes (3).

Vertical farming could provide a number of solutions to the current issue of limiting the effects of industrial-scale agricultural land use on the global climate, providing a means of more sustainable crop production. Vertical farming has its roots in the rudimentary hydroponic systems first developed by the ancient Egyptian (4th century), Chinese (12th century), and Aztec (14th century) civilizations. Vertical farming systems (VFS) were made possible through the development of modernized greenhouses, artificial lighting, and soilless growing techniques.

While the term "vertical farming" was coined by geologist Gilbert Ellis Bailey in 1915 (4), the modern concept as we know it today was developed by Dickson Despommier in 1999. The first truly competitive vertical farming enterprise on the market emerged in Singapore in 2012.

In 2023, the size of the global vertical farming market was estimated to be approximately US$7 billion, and this market is expected to grow by another 20% by 2030 (5). As the effects of our changing climate are becoming more evident, this growth is mainly attributable to the increasing interest in more sustainable production systems and models. It is therefore no coincidence that, in 2023, vertical farming start-ups raised about US$50 million, representing a 65% increase from 2022. In early 2024, the world's largest vertical farm, covering about 14,500 cultivable square meters, opened in Lydney, Gloucestershire, in the United Kingdom. Despite Europe dominating the vertical farming market in terms of sales and with a share of more than 30%, European agricultural policies have shown only modest support of new and more innovative agricultural production systems. Conversely, federal policies in the United States are funding the development of indoor agriculture much more generously. However, the produce grown in VFS cannot be labeled as organic in either Europe or the United States, as it does not comply with the definition of organic food due to the complete absence of soil (6).

The potential of vertical farming

Today, almost 60% of the world's population lives in urban and peri-urban areas (7). This number is set to grow to 68% by 2050; by the same year, the world's population is projected to reach 9 billion (8). The greatest demand for food will therefore come from people living in urbanized areas. Crop production via VFS could significantly increase in importance as rapid urban population growth will inevitably come up against price and production volatility, seasonality, and poorly functioning supply chains, aspects that will limit, both in physical and economic terms, the availability of fresh vegetables (9). Vegetable production via vertical farming would also guarantee greater resilience to catastrophic events that threaten supply chains, such as future pandemics and extreme weather events.

Open field crop production, too, is more negatively affected by uncertainties and risks directly associated with abiotic and biotic stressors and the effects of climate change than VFS. As the impacts from climate change worsen, the benefits of indoor cultivation may provide higher food security for future generations (10). The massive use of pesticides and fertilizers as a tool to ensure food security in open field production is also not sustainable considering the effects on both human health and the environment (11). Vegetable production through vertical farming does not require pesticides and herbicides, as growing conditions (day and night temperature, humidity, and light quantity and quality) are fully controlled. Water consumption, too, is greatly reduced, with vertical farming producing the same amount of vegetables but using only 5% of the water required for open field production (9). The integration of high-efficiency hydroponic systems allows for the application of only the macro- and micro-nutrients and water strictly necessary for plant growth. This limits water contamination and carbon dioxide emissions and reduces the economic costs associated with fertilizer production and use. The integration of techniques to biofortify vegetables with essential micronutrients beneficial for humans (iodine, selenium, zinc, and iron) would also be possible through the meticulous control of plant nutrition (12).

Further, it is estimated that more than a quarter of the world's population suffers from micronutrient deficiencies, so the ability to produce vegetables at a lower cost is a crucial step toward improving the health of people, particularly those with limited means and access to fresh produce. Building vertical farms in urban centers would also significantly shorten the supply chain, reducing transport-related carbon dioxide emissions and minimizing the time between harvest and consumption, ensuring maximum freshness of the product for the consumer.

How to overcome the critical issues in vertical cultivation?

Despite all the advantages, even the most ardent supporters of vertical farming admit that the enormous use of energy presents a serious obstacle toward the successful implementation of such production systems, particularly in parts of the world where access to reliable energy sources is not guaranteed. It is estimated that vertical farming occupies only 30 of the world's 500,000 hectares of land devoted to protected cultivation (13). Currently, we cannot yet produce large amounts of energy without impacting the environment; therefore the "energy problem" for vertical farming must not be neglected (14). Although renewable energy sources such as photovoltaic panels can become part of the solution, the environmental and financial costs associated with their production, transportation, installation, and disposal are often overlooked. In general, the overall supply of "green" electricity remains insufficient.

Another challenge is related to the lack of social acceptance toward the implementation of vertical farms. Consumers consider highly technological production methods as "unnatural" and potentially harmful to human health. This misconception is the result of a lack of information about the concepts behind soilless cultivation. It is therefore paramount to improve communication with consumers, clearly explaining the advantages and disadvantages of indoor cultivation (15).

Vertical farms should be understood as facilities that are able to produce horticultural species within highly controlled environments, erasing the impact of negative external conditions (extreme temperatures, polluted soils, unavailable and/or poor-quality irrigation water, etc.). Especially in these contexts, growing crops completely untethered from external conditions would prove to be a benefit that would outweigh the associated energy costs.

In this scenario full of contradictions, the lead article by Kaiser et al. (16), "Vertical farming goes dynamic: optimizing resource use efficiency, product quality, and energy costs", presents in detail the advantages of dynamic control over growth environment parameters in vertical farming, with the aim of reducing costly energy use. They specifically describe how making changes to the growing environment, in addition to modulating (positively or negatively) the development and physiology of the crop, can be a useful tool for increasing the cost-effectiveness of vertical farming by taking advantage of changes in electricity prices. Therefore, it will be necessary to define efficient models for dynamic control of the growing environment (light intensity and quality, temperature, humidity, and carbon enrichment). The use of advanced sensor technology would enable growers to make decisions on efficiency in terms of both yield and energy consumption. Unstoppable technological advances such as machine learning, the development of nanometer sensors, and the latest modeling approaches bode well toward such a development. This timely article by Kaiser et al. has been published at a crucial historical moment for the future of vertical farming, as more research into strategies such as dynamic control could greatly minimize the associated limitations of such sustainable production systems.

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