

Synthetic Biology in Vertical Farming; An Unexplored Path

by Zoe Triantafyllidou



What does a vertical farming system look like **in reality**?

Imagine a world where agriculture thrives in the heart of our bustling cities, transforming urban landscapes into lush green havens.

Synthetic biology and vertical farming are at the forefront of this agricultural revolution, poised to redefine our food systems in the face of unprecedented challenges like urbanization, environmental sustainability, and global food security.

Through the art of genetic engineering, synthetic biology empowers scientists to modify organisms with precision, enhancing vital traits such as crop yield, resilience, and nutritional value. Meanwhile, vertical farming offers a groundbreaking solution by cultivating crops in controlled, stacked environments, dramatically reducing land use and water consumption while ensuring that fresh, nutrient-rich produce is accessible right at our doorstep.

Join me on a journey to explore the dynamic intersection of synthetic biology and vertical farming, where the future of agriculture unfolds in extraordinary ways.

For all of you, curious investigators, who want to deepen into the world of synthetic biology...

Synthetic biology is an interdisciplinary science combining principles from biology, engineering, and data science to create organisms with modified or entirely new functions.

Synthetic biology includes gene editing and metabolic pathway engineering. CRISPR-Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats) is a breakthrough tool allowing precise DNA modification to offer different functions to the modified cell. In agriculture, this technology is used to introduce, delete or alter specific genes to create plants with attributes like improved growth rates, higher nutritional content and increased resilience to environmental stress conditions. Additionally, metabolic pathway engineering allows scientists to alter biochemical processes within plants, optimizing resource usage, photosynthesis and nutrient absorption, which seems to be helpful for their daily growth.

In agriculture, synthetic biology enables the creation of crops that are more resistant to pests, thrive in extreme conditions, or are fortified with additional nutrients. Thus, scientists have successfully inserted genes from resilient plants into staple crops, creating drought-tolerant or pest-resistant varieties.

This is something that [AeroFarms](#) is working on these years in order to bring about a change in the sector using synthetic biology fundamentals.

Biofortification is another promising application, where genetic modifications enhance the nutritional profile of crops, such as rice enriched with Vitamin A. These applications are especially critical in countries facing malnutrition or their own harsh growing conditions.

But how is synbio already used by companies on the field?

Modern synthetic biology relies on specialized tools and software for DNA analysis and design.

- [Benchling](#) is a software tool that I have been exposed to some days ago and I found out that has outstanding properties. It is a cloud-based platform, allows researchers to visualize and plan gene edits, map metabolic pathways, and collaborate on genetic designs.

💡 Remember: STAY CURIOUS AND PUSH YOUR LIMITS 💡

“Choosing an Unconventional path will lead you to Unconventional success”

-Hari Mahesh, TKS program Director

So... it's time to learn!

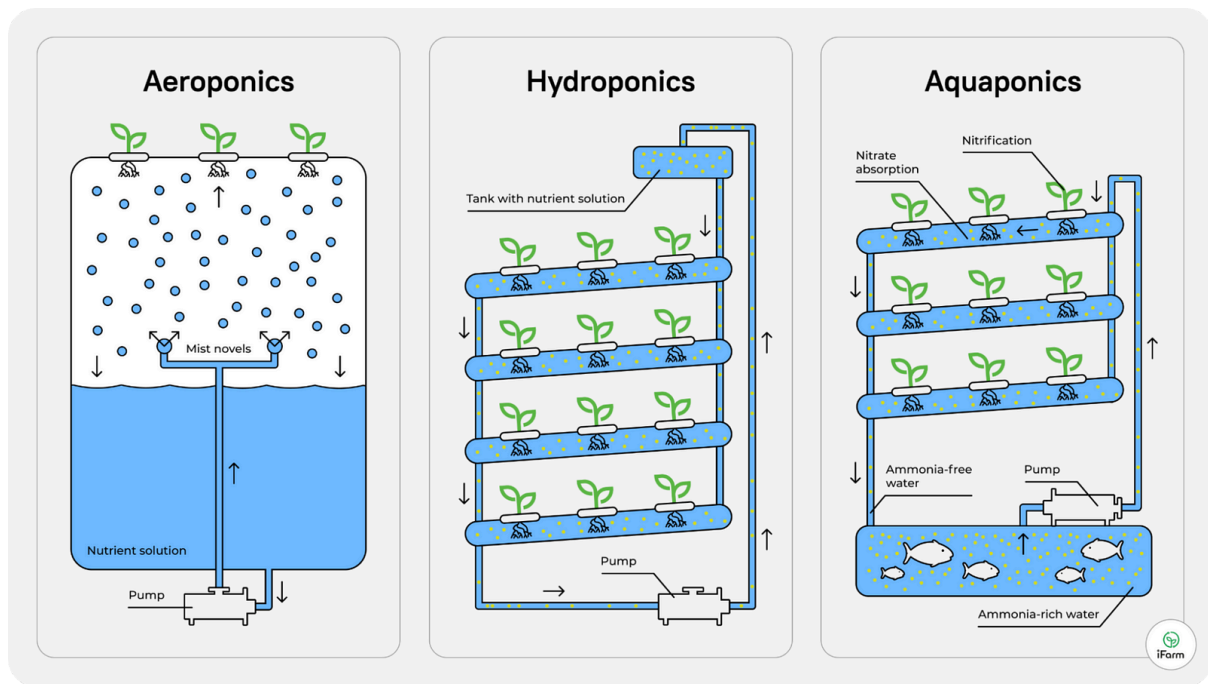


Vertical farming, in which plants grow in vertically stacked layers within a controlled environment, is designed to produce high yields with minimal resource usage. Vertical farms employ various systems to grow plants, which are divided into different categories.

Hydroponics, a water-based growing technique, delivers nutrients directly to plant roots without soil, conserving water and supporting rapid growth.

Aeroponics, where plants' roots are misted with a nutrient solution, maximizes water efficiency and nutrient absorption.

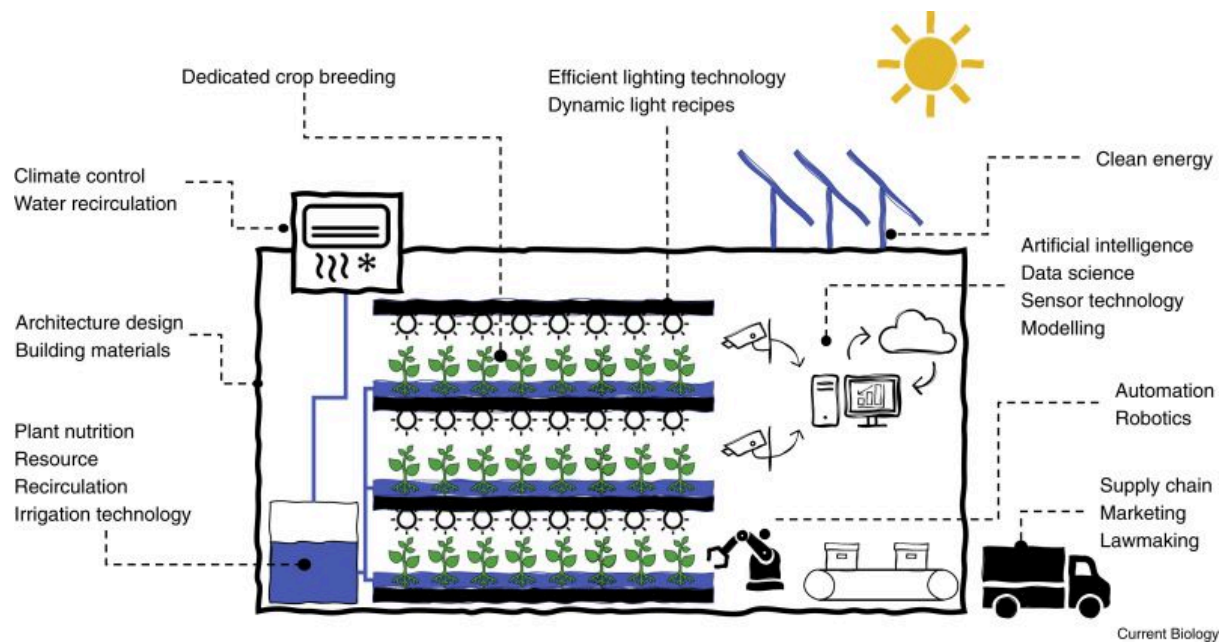
Aquaponics, merges hydroponics with aquaculture, using fish waste as a nutrient source for plants in a closed-loop system that reduces waste and water usage.



There is a division of the components of such a unit and each component has a different role. The success of vertical farming depends on precise environmental control systems.

LED lighting systems (light source) are designed to emit specific wavelengths—such as blue and red light—to optimize photosynthesis. Advanced LED systems like *Philips GrowWise* allow fine-tuning of light intensity and spectrum based on each crop's needs. *Climate control systems* use sensors to regulate temperature, humidity, and CO₂ levels, maintaining stable growth conditions. Finally, *nutrient delivery systems* in hydroponic and aeroponic setups ensure plants receive the exact nutrients they need, minimizing waste. These are found behind the climate control system of the unit.

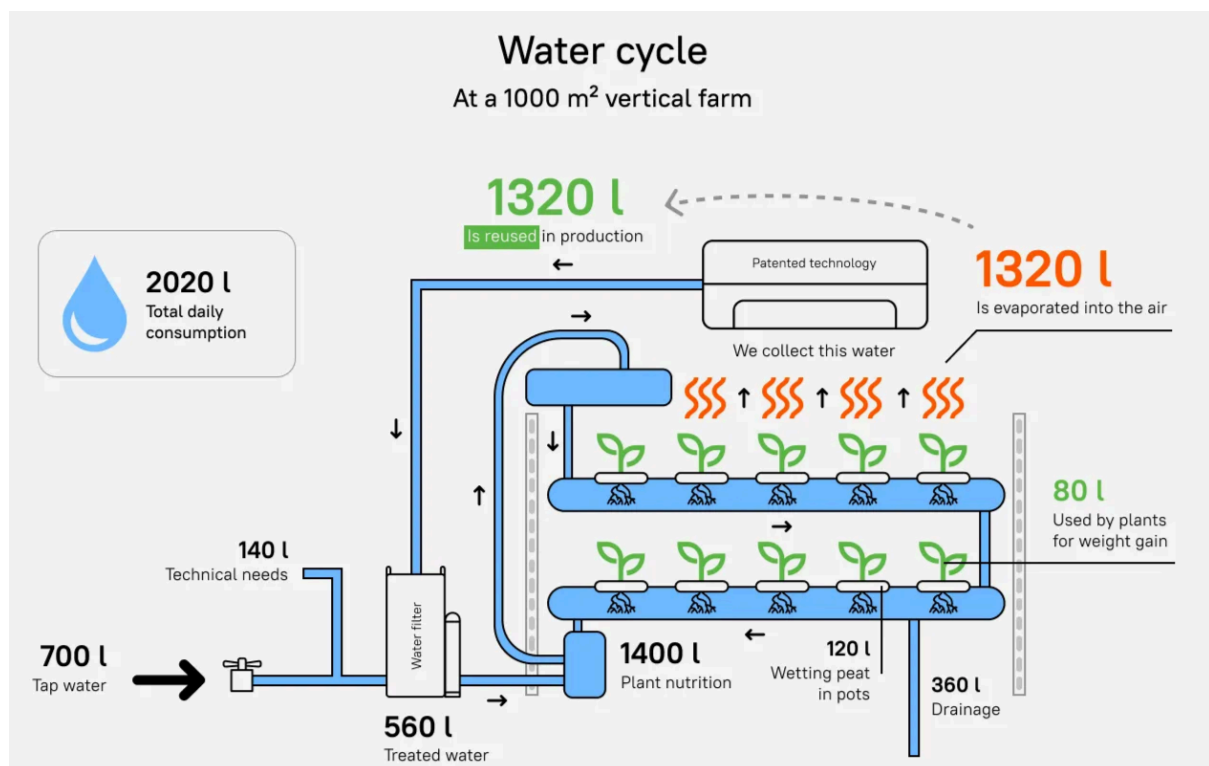
Vertical farms use software to monitor and adjust environmental factors in real-time (AI and monitoring system). *Argus Controls* automates lighting, temperature, and nutrient delivery to support each growth cycle precisely. Additionally, AI-powered platforms like *AgriFORCE* optimize every aspect of vertical farming, using machine learning to increase yields and reduce resource usage.



Diagrammatic example of integrated systems

The remnant of the water used during the procedure of the vertical farming units' plants cultivation is recycled and reused for the next time that this exact procedure is conducted, so the water doesn't get wasted. This is in the environmental benefits of the establishment of those units in our life.

The following data show how much water these units consume...



In contrast to the common agriculture where:

It consumes between 5.000 and 10.000 L of water daily (depending on the type of plant), which is around 5x more than the vertical farming system choice. While farms around the world account for 70% of all water that is consumed annually.

Of that 70% used by farmers, 40% is lost to the environment due to poor irrigation systems, evaporation, and overall poor water management.

Crop	Crop water need (mm/total growing period)
Alfalfa	800-1600
Banana	1200-2200
Barley/Oats/Wheat	450-650
Bean	300-500
Cabbage	350-500
Citrus	900-1200
Cotton	700-1300
Maize	500-800
Melon	400-600
Onion	350-550
Peanut	500-700
Pea	350-500
Pepper	600-900
Potato	500-700
Rice (paddy)	450-700
Sorghum/Millet	450-650
Soybean	450-700
Sugarbeet	550-750
Sugarcane	1500-2500
Sunflower	600-1000
Tomato	400-800

Types of plants and their consumption of water


Alright, guys, don't rule it out from the beginning only because it's something new. Let's consider its benefits for a while...

On the environment?

Vertical farming has the potential to address several environmental issues. By growing crops in stacked layers, vertical farms reduce land use by up to 99%, sparing natural habitats and preserving biodiversity. These systems also save water: hydroponic and aeroponic methods recycle water, using only a fraction of the water required by traditional farms. Placing vertical farms in urban areas reduces the carbon footprint associated with food transportation. However, these farms require significant energy for lighting and climate control, a drawback that can be also mitigated by integrating renewable energy sources, the future of energy!

What about society?

By providing year-round access to fresh produce, vertical farms bolster food security in urban areas and reduce dependency on distant farms. Cities can become more self-sustaining, producing their own fresh food locally and creating jobs in agriculture technology. Challenges remain in public acceptance, as some consumers are wary of genetically modified organisms or food grown outside natural environments. Education on these technologies can help increase acceptance.

 **A question of yours could be; If it brings such a positive impact on our lives, why hasn't it been established widely since today?**

Why haven't I heard it before?

Despite their benefits, vertical farms face some challenges that prevent it from developing and establishing itself in the market as the other agricultural systems have achieved.

The initial investment costs for setting up a vertical farm are high, covering specialized lighting, climate control, and automation systems. While long-term labor savings offset some costs, the capital needed remains a barrier. Energy consumption for lighting and temperature regulation is another concern, though energy-efficient LEDs and renewable power sources help mitigate this. Additionally, technological and regulatory barriers hinder widespread adoption,

as current crops are not optimized for vertical farms, and existing food regulations by the governments aren't always suited to indoor or genetically modified plants.

How can synthetic biology change this situation by being applied to vertical farming systems?

The integration of synthetic biology in vertical farming opens exciting possibilities.

1. Enhancing Crop Yields and Nutritional Value

Gene editing can boost yield by enabling faster growth cycles. For example, CRISPR-modified lettuce varieties grow more quickly, allowing for multiple harvests within a single season. Biofortification also enables crops to be engineered with higher levels of essential vitamins and minerals, providing nutrient-dense options for consumers.

2. Improving Plant Resilience

Synthetic biology enhances plant resilience to indoor farming's specific challenges, like high humidity and fluctuating light. Through targeted gene editing, researchers develop crops that withstand these conditions better, allowing for optimized indoor growth.

3. Novel Crop Varieties Suited for Indoor Farming

Synthetic biology can create crops specifically tailored for vertical farms. For instance, scientists can modify plants to reduce height or increase root efficiency, allowing denser planting and optimal space usage. These modifications make vertical farming more efficient and versatile.

Ethical Considerations?

As in every upcoming sector, so in this one, there seem to exist concerns by scientists and governments regarding the moral restrictions of the application of vertical farming in our lives.



Image by [Unsplash](#)

Ecological Risks and Biosafety

Genetic modifications in synthetic biology can lead to unintended ecological consequences. For example, a genetically modified crop might escape into the wild and crossbreed with wild relatives, disrupting local ecosystems and threatening biodiversity. Additionally, crops engineered to resist pests may inadvertently foster the evolution of resistant pest populations, leading to a potential increase in chemical controls. This cycle can have adverse environmental effects, raising concerns about the long-term sustainability of these agricultural practices.

Food Sovereignty and Justice

The biotechnology industry is often dominated by a few large corporations, leading to potential issues surrounding food sovereignty. This concentration can result in local farmers and communities losing control over their food systems, as they may become reliant on patented seeds and technologies that are economically prohibitive. Moreover, there is a risk that the benefits of synthetic biology and vertical farming may not be equitably distributed, leaving

communities in developing regions without access to advanced agricultural technologies and exacerbating existing inequalities in food security.

Ethical Considerations of Genetic Modification

Public perception and trust in genetically modified organisms (GMOs) can be a significant barrier to the adoption of synthetic biology in agriculture. Skepticism often arises from a lack of understanding of the technology or from concerns regarding the safety of GMOs for human health and the environment.

Furthermore, the moral status of engineered organisms raises philosophical questions; some ethical frameworks argue that genetically modified organisms possess intrinsic value and that their manipulation should be approached with caution.

Impact on Traditional Farming Practices

The rise of vertical farming and synthetic biology may disrupt traditional agricultural practices, threatening the livelihoods of small-scale farmers who rely on conventional methods. Additionally, farming is often deeply intertwined with cultural identity and community values. The introduction of synthetic biology could undermine these traditional practices, along with the associated cultural heritage, creating a gap between modern agricultural practices and historical methods.

Resource Consumption and Sustainability

While vertical farming can significantly reduce land and water usage, it often relies heavily on artificial lighting and climate control, resulting in high energy consumption. This raises ethical questions regarding the source of this energy, particularly if it comes from non-renewable resources. Moreover, the production of genetically modified seeds and the maintenance of vertical farms can contribute to carbon emissions and environmental degradation, necessitating a critical examination of the overall sustainability of these technologies.

Regulatory and Governance Challenges

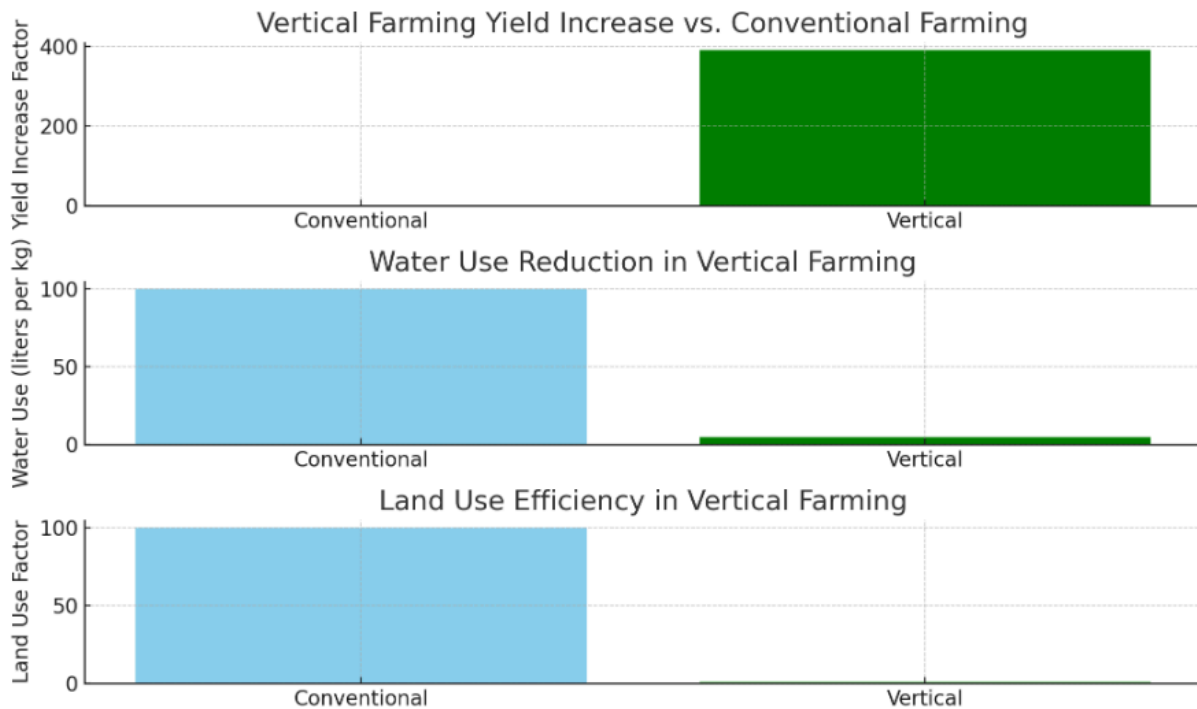
Existing regulatory frameworks may not adequately address the unique challenges posed by synthetic biology and vertical farming, highlighting the need for updated policies that ensure the safe and ethical deployment of these technologies. Additionally, varying regulations across countries regarding GMOs

and synthetic biology can lead to potential trade issues and concerns over biosecurity, complicating the global agricultural landscape.

What does the future of this technology look like?

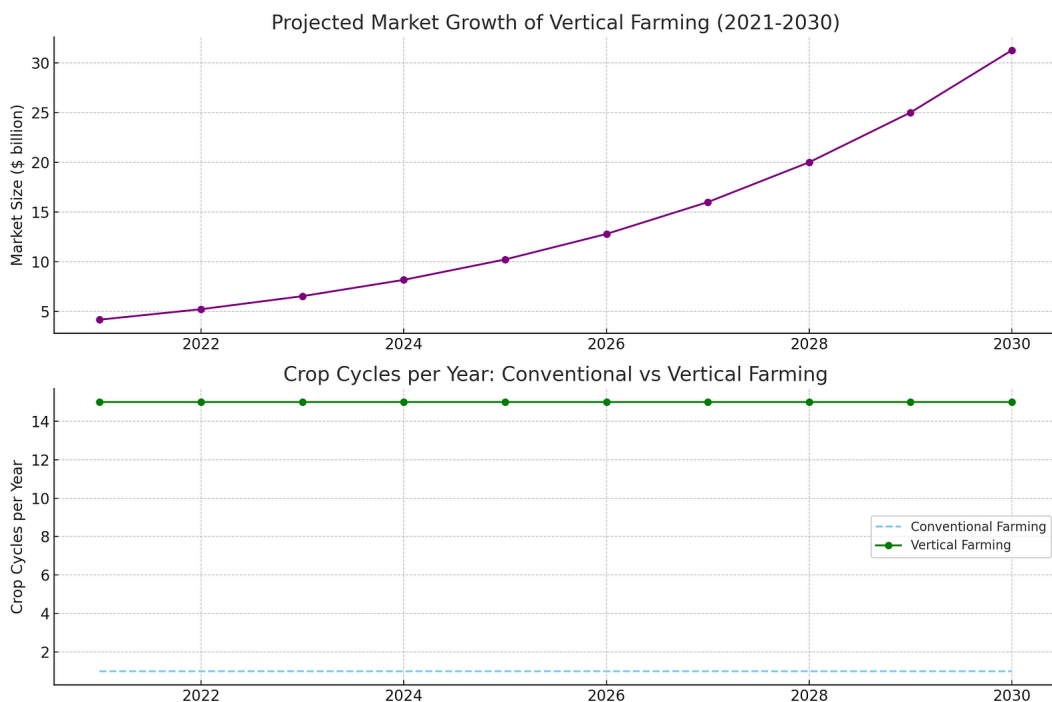


The future of synthetic biology and vertical farming is promising. AI and machine learning are likely to play an increasing role in optimizing plant growth by analyzing data in real time. Additionally, advancements in genetic engineering, such as self-fertilizing plants, could reduce the need for added nutrients. Moving forward, a roadmap for integrating synthetic biology into mainstream agriculture should include investment in renewable energy, developing optimized crop varieties, and public education to drive acceptance. These innovations hold the potential to redefine food production by enabling sustainable, year-round, and locally accessible food.



These bar charts provide a clear representation of how vertical farming drastically improves efficiency across yield, water, and land usage, underscoring its potential to transform food production in resource-limited environments.

Here is a visual comparison highlighting the quantitative benefits of vertical farming on projected market growth:



Market Growth—Comparison of vertical VS. conventional farming

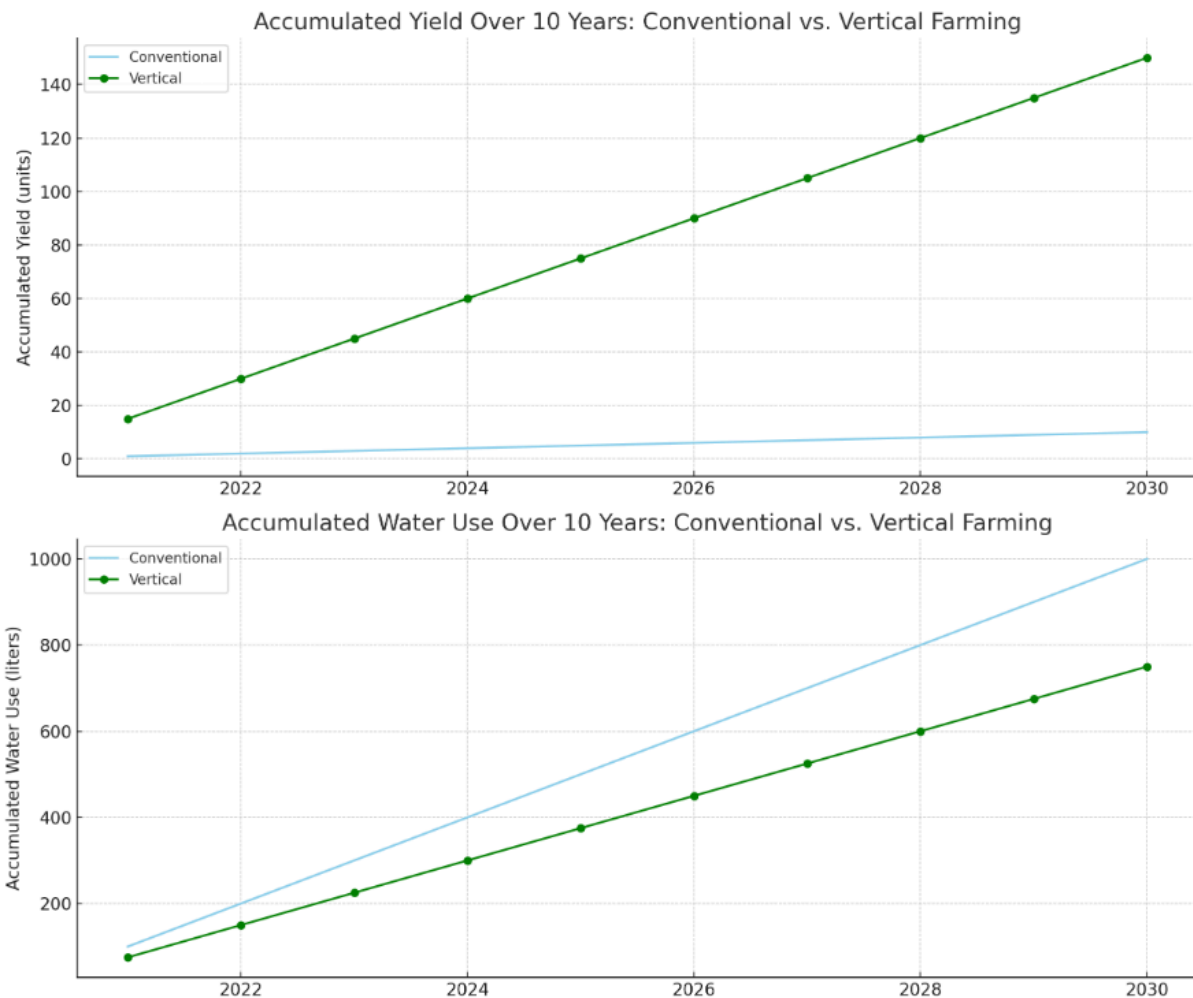
Market Growth Projection: Based on a projected 25% compound annual growth rate (CAGR), the vertical farming market could grow from \$4.2 billion in 2021 to nearly \$33 billion by 2030. This rapid growth highlights increasing demand for efficient and sustainable food production solutions.

Annual Crop Cycles: By operating year-round, vertical farms can achieve **15–20 crop cycles annually** compared to only 1–2 in traditional farms. This increase in cycles, combined with a stacked layout, boosts production on a per-area basis significantly.

Productivity Gains

Yield Comparison: Vertical farming can produce up to **390 times more yield/square foot** than traditional field farming. For instance, AeroFarms' vertical farm in New Jersey currently achieves 390 times the productivity of a comparable field farm, focusing on leafy greens and herbs.

Accumulated Yield: Over 10 years, vertical farming significantly outpaces conventional farming in accumulated yield due to the ability to have multiple crop cycles per year (up to 15 for vertical vs. 1 for conventional). This highlights the efficiency of vertical farming in meeting high production demands.



[Here are additional visualizations showing the cumulative resource savings and production over a decade for vertical versus conventional farming:](#)

Water Use Efficiency

Water covers 71% of the world's surface, yet only 3% is suitable for drinking and farming—and water use is growing at more than twice the rate of population increases. If we don't change our habits, global demand for water could increase by 50% by 2030.

Water Savings: Vertical farms use up to **95–98% less water** than traditional methods. For example, a typical farm requires around 100 liters of water to produce a kilogram of lettuce, whereas vertical farms use only 5 liters for the same yield.

Closed-Loop Systems: Many vertical farms use closed-loop irrigation systems to recycle water, contributing to this drastic reduction, which is particularly valuable given that agriculture accounts for about 70% of global freshwater usage.

Agriculture is both a cause and a casualty of water scarcity. It accounts for an estimated 70% of global water withdrawals, with freshwater resources heavily stressed by irrigation and food production. This also results in soil salinisation, leading to further declines in crop quality. According to the United Nations, China is one of 13 countries contending with serious water scarcity, having 21% of the world's population, but only 6% of its freshwater. Overall, China's per capita availability of water is just 25% of the world's average, and more than 400 Chinese cities are short of water (1).

Example – Water Usage:

- Conventional farming: **300–500 liters per kg** of produce.
- Vertical farming: **30–70 liters per kg** of produce (up to 90% less water).

Land Use Reduction

Land Requirements: Vertical farms require up to **99% less land** than conventional farms due to their stacked structures. This compact design allows vertical farms to be placed in urban settings, reducing the land pressure on rural areas and freeing up more land for other uses.

Urban Accessibility: By bringing farms into cities, vertical farming also cuts down on food miles, potentially reducing transportation emissions by **30–40%** and increasing access to fresh produce for urban populations.

Calculation:

- **Conventional Farming:** Typical yield for crops like lettuce: **10–15 tons per hectare per year**. | Land required: **5–10 square meters per kg** of lettuce.
- **VS. Vertical Farming:** Typical yield for crops like lettuce: **200–300 tons per hectare per year**. | Land required: **0.1–0.5 square meters per kg** of lettuce.

→ Results:

- For every 1 hectare (10.000m²) of vertical farming, you can produce approximately 300 tons of lettuce.
- Conventional farming might require 10 hectares to produce the same amount, showcasing a **land use reduction of up to 90%**.

Vertical Farming Structure:

- **Footprint:** Vertical farms can produce the same amount of food as several acres of traditional farmland in a much smaller footprint, often within a single building.
- **Layers:** Many vertical farms utilize multiple layers (often 5–12) to maximize space.

Energy Use and Cost Efficiency

Energy Reduction Strategies: Researchers are developing methods to manage electricity costs by adapting lighting intensity based on demand and electricity prices. By optimizing light schedules, vertical farms can reduce lighting costs by up to **12%** without affecting crop yields.

Energy Demand: Vertical farms still face high energy demands, particularly from artificial lighting. Innovations in LED lighting and solar-powered systems, however, have shown promise in reducing this load by as much as **20–30%**, making vertical farming increasingly viable on a larger scale.

Market and Economic Impact

Market Size and Growth: The vertical farming market was valued at around **\$4.2 billion in 2021** and is projected to reach **\$33 billion by 2030**, growing at a compound annual growth rate (CAGR) of approximately **25%**.

Potential Pricing Impact: As vertical farming technology scales and becomes more efficient, costs are expected to decrease, potentially lowering produce prices by **30–40%** over the next decade. This price drop could make vertical farm produce more competitive with conventionally grown alternatives, especially for high-demand crops like leafy greens and certain fruits.

Summary of everything above:

- **Yield:** Up to 390x productivity per square foot.

- **Water Use:** 95–98% reduction.
- **Land Use:** Up to 99% less than traditional farming.
- **Energy Cost Savings:** Potential for 12% reduction with dynamic lighting.
- **Market Growth:** Projected \$33 billion market size by 2030 with 25% CAGR.

→ This data illustrates that vertical farming holds potential to significantly reshape food production, making it more efficient, sustainable, and adaptable to urban environments and resource-scarce regions.

Conclusion:

The combination of synthetic biology and vertical farming offers a transformative vision for agriculture. Leveraging genetic engineering alongside advanced farming systems, we can tackle pressing issues like food security, environmental sustainability, and urbanization. With the ability to reduce land and water use, minimize carbon emissions, and enhance nutritional quality, synthetic biology and vertical farming stand as powerful tools for a more resilient, nutritious, and sustainable food system. As these technologies evolve, they promise to reshape our relationship with food production and the environment, bringing a brighter, more sustainable future within reach.

Finally, who am I?

My name is Zoe and I'm a high school student in Greece. I recently got accepted into TKS and this is an article on one of the technologies I'm now exploring!

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