

Vertical Farming: Growing Crops Without Soil

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Abstract

Vertical farming intensive crop production in stacked layers using hydroponics, aeroponics or other soil-free substrates promises to re-localize fresh vegetables, reduce freshwater use and shield production from weather volatility. At the same time, it faces hard engineering and economic trade-offs: the artificial environment depends on electricity, capital and skilled operation. This article takes an evidence-minded, practitioner-oriented look at the technology, the agronomy that makes it work, the environmental and economic trade-offs and the realistic pathways that let vertical farms be both productive and sustainable. I summarize where vertical farming offers clear wins (leafy greens near cities), where it still struggles (energy- and capital-intensity; broad scale staple production) and what design and policy choices reduce risk and improve outcomes. The goal is not to sell a hype cycle but to give a clear, human account that helps farmers, planners and local food champions decide when and how vertical farms belong in their toolbox.

Keywords: vertical farming, plant factory, hydroponics, aeroponics, LED lighting, energy efficiency, water use, life cycle assessment, urban agriculture, controlled environment agriculture

Introduction

Vertical farming (VF) bundles technologies that have been in the lab for decades precise light spectra, automated nutrient delivery, climate control into commercial operations designed

to grow food vertically, close to consumers. The model is attractive: year-round production, minimal pesticide use, short supply chains and the capacity to place production in dense urban areas or food-insecure neighborhood. Yet the same features that make VF reliable artificial lighting, HVAC and continuous monitoring also create energy bills and capital requirements that are materially different from field agriculture. Understanding those trade-offs is essential if vertical farming is to deliver meaningful sustainability, not just novelty.

What we mean by vertical farming (short taxonomy)

Vertical farms range from small containerized units and supermarket micro-farms to multi-story industrial facilities. Common system types include:

- **Hydroponics (NFT, ebb-and-flow, troughs):** roots bathed in nutrient solution; widely used for lettuce and herbs.
- **Aeroponics:** roots intermittently misted with nutrient solution very water-efficient and space-efficient but technically demanding.
- **Substrate-based systems:** grow media in trays on stacked racks; useful for some fruiting crops and seedlings.
- **Hybrid systems and container farms:** modular units using similar core components but optimized for portability or low-capex deployment.

Across these types, the core engineering modules are lighting (LED arrays), racks and conveyance, nutrient dosing and recirculation, HVAC and dehumidification, sensors and controls and post-harvest handling.

The core promise: land, water and proximity

Vertical farms compress productive area by using vertical space, which reduces the land footprint per kilogram of produce and opens the possibility of farming in brownfield warehouses and urban rooftops. Water-use advantages are real and large in many cases: controlled, recirculating systems can cut irrigation volumes dramatically single studies and facility reports commonly show water-use reductions in the tens of percent up to ~67% or more compared with some conventional systems, because evapotranspiration is controlled, runoff is eliminated and dehumidifier condensate can be recovered. Beyond resource metrics, proximity to market changes the value chain: freshness improves shelf life and reduces transport emissions and waste. For leafy greens and herbs high-value, quick-turn crops these advantages are particularly strong.

The counterweight: energy and environmental trade-offs

Energy is the central engineering and environmental constraint in many vertical farms. LED lighting and climate control dominate operational electricity; reported specific electricity uses vary widely across facilities and studies because system design, local climate, heat-

recovery options and scale all matter. For example, careful benchmarking studies for lettuce show typical specific energy consumption in the order of 10–18 kWh per kg in some high-efficiency systems, while real-world facility surveys can report higher averages depending on local practice and inclusion of heating/cooling loads. That dispersion is important: an energy-efficient VF with smart lighting and heat recovery can be competitive on environmental grounds, while an energy-inefficient layout can produce much higher per-kg footprints.

Life-cycle assessments reflect that nuance: some LCAs of commercial vertical farms find lower greenhouse-gas emissions than conventionally sourced produce when electricity is low-carbon or when transport and land-use displacement are counted, but other impact categories (e.g., cumulative energy demand, embodied materials) can be higher. Outcomes are therefore context dependent: energy mix, building reuse and heat recovery are decisive variables.

Economics and business models: why electricity price and scale matter

Vertical farms are capital-intensive and highly sensitive to operational costs. Recent techno-economic work shows that small shifts in electricity price change unit costs noticeably: lowering grid electricity by a few US cents per kWh reduced modelled production costs from roughly \$3.77 to \$3.51 per kg in one study, underscoring the sensitivity of the business case to local energy pricing and energy-efficiency investments. This is why many operators optimize for high-value crops, co-locate farms near premium markets, or invest in on-site renewables and heat-recovery systems. Business models that have shown traction include: direct-to-retail contracts (supermarkets, restaurants), local hospitality supply, subscription boxes and municipal procurement. Smaller modular farms shipping-container or grocery-store systems often emphasize lower capex and community integration rather than pure cost competitiveness with field-grown bulk vegetables.

Crop suitability: where vertical farming shines (and where it doesn't)

Vertical farming's sweet spot is rapid-turn, high-value, compact crops leafy greens, salad mixes, herbs, microgreens and seedlings. These crops fit well because they have short cycles, high value per unit area and respond well to light-quality tuning. Attempts to grow fruiting crops (tomato, strawberry) or coarse grains have had limited economic success because they require more space, longer cycles and greater energy per unit of edible yield.

Agronomically, success depends on tight control of root environment (EC, pH), consistent light regimes with optimized spectra and disease prevention through biosecurity and routine sanitation. Seed quality, nursery management and careful SOPs for nutrient solution management are non-sexy but decisive.

Operations: practical design choices that matter

Some operational principles consistently separate resilient farms from fragile ones:

- **Design to heat-balance:** lights add heat; reclaiming that heat for space or water heating and using free cooling where possible reduces net energy.
- **Right-size racks for human access:** overly dense rack layouts reduce labour ergonomics and raise handling costs.
- **Recirculate with care:** closed nutrient loops save water but concentrate pathogens and trace elements; a small, controlled exchange and periodic monitoring keep solutions safe.
- **Modular redundancy:** duplicate critical pumps, dosing lines and a dependable backup power plan; small failures scale quickly in dense systems.
- **Data-driven control but human oversight:** automation reduces routine errors, but skilled operators who understand plant signals remain essential.

Innovations improving the economics and footprint

Several technical and business innovations are lowering barriers:

- **High-efficacy LEDs and dynamic spectra:** increasing light-use efficiency and tailoring spectra to developmental stages reduces wasted photons.
- **Advanced controls and machine learning:** closed-loop nutrient and climate control cut losses and improve consistency.
- **Integration with renewables and waste heat:** pairing VF with on-site PV, combined heat and power, or district heating can flip the life-cycle numbers.
- **Product diversification:** selling seedlings, specialty varieties or agri-tourism experiences spreads risk.
- **Modular scaling:** replicating validated modules reduces biological start-up risk and helps manage capex deployment.

Environmental nuance: when vertical farming helps cities and when it doesn't

Vertical farms are powerful tools for specific urban sustainability goals: reducing transport, supplying fresh produce in food deserts and enabling year-round supply where field production struggles. Market analysts and industry projections also indicate rapid sector growth: industry reports estimate the global vertical farming market at roughly \$6.9 billion in 2024 with strong projected growth a sign of investor and buyer interest, though not a guarantee of profitable outcomes for every operator. But sustainability claims must be qualified. A VF that runs on fossil-heavy grid electricity without heat reclamation can have a larger per-kg energy footprint than a nearby greenhouse supplied with low-carbon heat. Policymakers and investors need to ask site-specific questions: what is the local grid carbon intensity? Can the farm capture heat or pair with renewables? Is the target market willing to pay a premium for proximity and year-round supply?

Social and planning considerations

Vertical farms can create local jobs, enable training in new agritech skills and shorten supply chains. They also raise questions of equity: capital-heavy models can concentrate benefits among well-funded firms unless programs intentionally lower entry barriers (shared facilities, municipal partnerships, grants or concessional finance). Urban planning matters, too zoning, electricity tariffs and waste-management rules shape viability.

Practical checklist for anyone planning a vertical farm

1. Start with the market secure purchase agreements before scaling.
2. Model energy and heat flows early; treat energy as a core input, not a minor cost.
3. Pilot in modular blocks to learn the biology before expanding.
4. Prioritize labour ergonomics and sanitation in rack and facility layout.
5. Invest in sensor redundancy and simple, actionable dashboards for operators.
6. Explore co-benefits waste heat reuse, on-site composting of residues, or selling transplants.
7. Plan for regulatory compliance on water discharge, fertilizers and food safety from day one.

Table: practical components, considerations and quick tips

S.no.	Component / Consideration	What it does	Practical tip
1	Lighting system (LEDs)	Drives photosynthesis and influences morphology	Use high PPF LEDs with dimming and stage-specific spectra
2	Racking & access	Maximizes vertical area	Design for ergonomics and maintenance aisles
3	Nutrient dosing & recirculation	Delivers fertilizer; reduces water use	Automate dosing and log EC/pH every shift
4	Reservoir & water treatment	Stores and conditions nutrient solution	Filter and UV-sterilize make-up water; schedule exchanges
5	HVAC & dehumidification	Controls temp and humidity	Reclaim heat from lights and dehumidifiers
6	Pumps & plumbing	Circulates solution	Redundancy on critical pumps; easy isolation valves
7	Sensors & controls	Real-time monitoring	Use independent sensors for checks and alarm thresholds
8	Backup power	Keeps life-support online in outages	Size for life-support loads plus generator/fuel plan
9	Seedling nursery	Ensures uniform starts	Centralize propagation with strict sanitation
10	Pest & disease management	Prevents outbreaks	Strong entry biosecurity and routine surface sanitation

11	Harvest & post-harvest area	Washing, packing, cold chain	Design one-way flow to reduce contamination risk
12	Data logging & traceability	Food safety and process improvement	Keep batch records and lot traceability
13	Automation (conveyors, robotics)	Reduces labour for repetitive tasks	Start small; add automation after SOPs are stable
14	Water reuse & condensate recovery	Improves water efficiency	Capture dehumidifier condensate as buffer make-up water
15	Waste management	Handles spent media and residues	Compost or anaerobic digestion where possible
16	Lighting control strategy	Photoperiod and PPFD management	Optimize DLI by stage; avoid round-the-clock lighting
17	Worker training	Human expertise for plant health	Invest in seasonal training and simple SOPs
18	Business model (B2B / B2C)	Revenue channels and margins	Lock in contracts with restaurants/retailers early
19	Energy optimization	Lowers OPEX	Variable speed drives, gravity flow, timed lighting cycles
20	Regulatory & food safety compliance	Market access and consumer trust	HACCP, local health permits and clear labelling

Conclusion

Vertical farming is not a one-size-fits-all solution; it is a calibrated tool that excels where space, freshness and controlled production offer premium value principally leafy greens and herbs sold near consumers. The sustainability case is conditional: with efficient LEDs, heat recovery, low-carbon electricity and modular, well-operated facilities, VF can reduce water use, shrink supply chains and lower some environmental impacts. But without those design choices, it can be energy-intensive and expensive. For practitioners and policy makers the sensible route is pragmatic: pilot small, measure everything (energy, water, labour), prioritize integration with renewables and heat recovery and match production to clearly defined local markets. When those facts guide design and finance, vertical farming becomes less a flashy experiment and more a reliable piece of a resilient, local food system.

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