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Technology adoption in the vertical farming industry

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Vertical farming has attracted substantial attention as a potential solution to land scarcity, climate volatility, and urban food supply challenges. Yet despite strong theoretical advantages and more than $10 billion in venture capital investment since 2015, many first-wave vertical farming companies have failed. This study examines how second-wave vertical farming firms that survived the industry downturn have adopted advanced technologies and how business considerations have shaped those decisions. Using a global survey of vertical farming companies combined with executive interviews and case studies, we analyze adoption across six technology domains: lighting, automation and robotics, sensing, artificial intelligence, water systems, and growing inputs. Our findings suggest a pattern of selective technology adoption driven primarily by return on investment and operational fit rather than technological sophistication. LED lighting and nutrient film hydroponic systems have become prevailing production standards, while high-cost automation, robotics, and AI show uneven adoption. Second-wave vertical farming companies emphasized pragmatic, modular technology strategies aligned with market demand, avoiding the capital-intensive technological investments that contributed to the failures of earlier venture-funded firms. By illuminating the business factors driving technology adoption, the study addresses a gap in the vertical farming literature.

KEYWORDS
automation and robotics, corporate strategy, digital technology, lighting, sensing technology, technology adoption, vertical farming, water recycling

Introduction

As the productivity gains of the resource-intensive Green Revolution of the 20th century dissipate, the global agricultural sector faces serious challenges meeting the food demand of a world population projected to reach 10 billion people by 2050 (Nikos and Bruinsma, 2012). The supply of arable land is essentially fixed, and deforestation to clear land for agricultural production eliminates carbon sinks vital for greenhouse gas mitigation (Sands et al., 2023). Declining soil fertility, shrinking nutrient stocks, rising water scarcity, and growing incidence of extreme weather events further limit the capacity of conventional terrestrial farming to fulfill global food demand in coming decades (World Food Program, 2025).

Amid these challenges, vertical farming (VF) offers significant promise as a source of global food production in the 21st century. The academic literature on CEA (Controlled Environment Agriculture) catalogs the theoretical benefits of VF: 365-day food production in enclosed structures unaffected by outside weather and seasonality; elimination of insecticides and pesticides; reduced water consumption; deployment in climate-stressed food deserts; relief of food insecurity in economically distressed communities (Avgoustaki and Xydis, 2020; Ragaveena et al., 2021; Nájera et al., 2022; Budavári et al., 2024).

Sowmya et al. (2024) note the potential efficiency gains of VF systems, whose precise control of environmental conditions (light, temperature, humidity) boosts crop yields. In a comparative field study in the United Kingdom and Spain, Gargaro et al. (2025) found that vertical farms achieved lettuce yields 24 times higher than conventional farms.

With rising urbanization (approaching 70 percent by mid-century), VF enables year-round cultivation of fresh produce near city consumers, lowering transportation costs, reducing carbon emissions, and mitigating supply chain volatility. VF also promotes urban revitalization through repurposing of abandoned buildings, shuttered factories, brownfield sites, and other underutilized spaces.

Vertical farming plays an important role in India and other emerging markets, serving to bolster food security, reduce consumption of water and fertilizer, and support climate-resistant urban agriculture (Policy Circle Bureau, 2025).

These attributes spurred a steady expansion of the global VF industry. The VF market generated revenues of $7.4 billion in 2025, and is projected to reach $22.0 billion by 2035 with a CAGR (Compound Annual Growth Rate) of 11.4 percent (Future Market Insights, 2025). The promise of VF also triggered $10 billion of venture capital investment in VF since 2015.

But the investment community's appetite for vertical farming has faded. Since peaking in 2022, VC funding of VF startups has sharply declined. The falloff of VC investments in VF parallels the decline in global venture funding of the broader agrifood technology sector, which peaked at $56.3 billion in 2021 then fell to $16 billion in 2024 (Marston, 2025).

Meanwhile, a number of established VF companies in the United States, Europe, and other regions have declared bankruptcy, undergone liquidation, or scaled back production. The list of failed VF companies includes Plenty (which had received $941 million in venture funding), AppHarvest ($712 million), and Bowery Farming ($475 million) along with Fifth Season, Freight Farms, Kalera, GrowUp Group, IronOx, and Vertical Future.

This paradox of strong theoretical promise alongside high business failure rate motivates the central question of this study:

> *What business factors drove the technology adoption strategies of second-wave VF companies that survived the early wave of failures in the industry?*

We distinguish between "first-wave" venture capital-funded VF companies founded primarily between 2015 and 2022 and "second-wave" firms that emerged or pivoted following the industry contraction. Our categorization of VF companies draws on the Technology Adoption Life Cycle (e.g., Moore, 2014) that distinguishes between "early adopters" (visionary entrepreneurs willing to take risks on potentially transformative technologies) and "early majority" (pragmatists emphasizing peer validation and proven return on investment). We use the "wave" term inspired by similar innovation waves in the industry-proximate CleanTech industry (Bessemer Venture Partners, 2022).

Our investigation led us to conclude that the high failure rate of the first-wave VF companies stemmed chiefly from large capital expenditures on complex technologies misaligned with market dynamics. These over-engineered, CapEx-intensive VF companies proved unable to compete with conventional food producers in price-sensitive commodity markets. By contrast, the second-wave VF companies have achieved profitable growth (sustaining earnings and improving margins) by anchoring technology decisions to demonstrated market demand, operational requirements, and capital discipline. By viewing technology adoption through the lens of business strategy, our research augments the extant literature on vertical farming.

Theoretical framework

We introduce two components of our theoretical framework: A technology adoption frame and an advanced technology review.

First, we draw on the Technology-Organization-Environment (TOE) framework (Tornatzky and Fleischer, 1990), which has been widely applied to technology adoption decisions across industries including agriculture (e.g., Nagy et al., 2025). TOE posits that three contextual factors jointly shape a firm's adoption of technology: the characteristics of available technologies, the internal attributes of the adopting organization, and the external environment in which the firm operates. In this paper, these three factors are shown to compensate for each other.

In this study, we use TOE as an interpretive framework for organizing and understanding technology adoption patterns rather than as a predictive model. Prior VF scholarship focused predominantly on the presumed effects of advanced technologies: e.g., the agronomic benefits of LED lighting, automation, sensing, and AI systems under controlled conditions. The literature is weaker on organizational factors (business model, financial resources, competitive positioning, operational platform) as well as environmental factors (market structure, capital availability, competitive dynamics). Our study addresses that gap.

Second, we review the literature on advanced VF technologies (lighting, automation and robotics, digital technology). While that literature provides valuable insights on commercial applications of VF technology, it leaves open the question of how business factors (competitive, financial, operational, strategic) drive the technology adoption decisions of company leaders. For this review, we used the search term "vertical farming technology" in ABI/INFORM to locate peer-reviewed academic articles published between 2022 and 2026.

Lighting technology

LEDs (Light Emitting Diodes) constitute the foundational enabling technology of VF. By generating uniform, photosynthetically active radiation in indoor structures, LED lighting supports year-round plant growth without dependence on natural sunlight. Insulated from weather changes and unaffected by day length, LEDs allow vertical farms to operate continuously regardless of climate or location. Through electronic controls, vertical farms can calibrate the intensity and wavelengths of LEDs to meet the photosynthetic requirements of individual plant varieties. LED lighting systems also provide operational efficiencies in vertical farms, emitting low heat levels that reduce cooling costs while enjoying long performance lifetimes (upwards of 50,000 h) that lower maintenance and replacement costs.

Research on VF illustrates the benefits of LED lighting technology. Hati and Singh (2021) cite field tests demonstrating that LED systems using continuous lighting achieve better photosynthesis rates, higher leaf count, and greater plant height than conventional farming methods. Avendano-Abarca et al. (2022) describe a VF experiment in Mexico where modifications of the proportions of blue and green LED lighting boosted plant growth and water-use efficiency in strawberry cultivation. A study by Budavári et al. (2024) found that the tailored light spectra of LED systems promote plant growth. LED lights also penetrate deep into thick plant canopies, supporting photosynthesis in lower leaves.

The energy efficiency of LEDs confers further advantages to vertical farms, where electricity consumption accounts for the largest share (40–50 percent) of operational expenses. A field study in Portugal indicated that the substitution of HBS (High-Pressure Sodium) lighting with LEDs yielded total energy savings of 10–15 percent (Pereira and Gomes, 2025). Through distributed renewable energy (e.g., solar photovoltaic panels) LED-based vertical farms can realize additional cost savings while lowering reliance on grid electricity. The intermittency of solar power may compromise the operational advantages of continuous LED lighting.

However, vertical farms can mitigate that problem by installing battery storage systems (e.g., lithium-ion batteries) whose costs are rapidly declining. Innovations in structural design promise additional gains in the energy efficiency of LED-based VF systems. Researchers in Singapore conducted a field experiment using prismatic light-redirecting panels. In this model, panels on the outer edges of plant racks passively channel sunlight to shaded central areas, augmenting LEDs with natural sunlight and lowering energy costs. This technique offers a practical, low-cost means of enhancing sunlight in multi-tiered VF systems (Lee et al., 2024).

The demonstrated benefits of LEDs have made this lighting technology a standard in the VF industry. Related lighting technologies are also gaining commercial traction in the industry. For example, color mixing systems (which comprise separate LED channels generating light in blue, green, red, and ultraviolet wavelengths) enable application of specialized “light recipes” for particular plants.

Other lighting technologies have yet to realize broad adoption in the VF industry. Zou et al. (2025) report on the application of PSO (Particle Swarm Optimization) for LED lighting in a vertical farm in Shanghai, China. Through PSO (a computational algorithm), researchers optimized the spectral quality and spatial distribution of lighting for strawberry cultivation. The experiment resulted in increased plant growth, higher yields, and reduced energy consumption. While PSO is widely used in research and engineering, it has not achieved commercial-scale deployment in VF.

Optical fiber daylighting systems supplement LED-generated light with natural sunlight. These systems comprise solar collectors (typically roof-mounted lenses or mirrors) that capture and concentrate sunlight, which is then transmitted through bundled fiber cables and diffused to the interior space of the vertical farm. Optical fiber daylighting delivers full-spectrum natural light to windowless zones of the facility, improving plant growth and lowering electricity costs. But such systems are ineffective in sun-deprived locations, while their high costs and operational complexity have hindered commercial adoption in the vertical farming industry (Vu et al., 2022).

Automation and robotics

Automation and robotics technologies are widely deployed in the VF industry. Such systems offer the following benefits.

Reduced labor costs

Operating in thin-margin commodity markets, vertical farms look to automation/robotics as an essential tool to reduce labor costs, which represent 25–30% of total expenses in the industry. The labor cost factor is particularly salient in North America, Europe, and other high-income regions facing shortages of agricultural workers. By automating repetitive tasks (seeding, transplanting, watering, fertilizing, harvesting, packing, bed cleaning, moving racks, trays, and trolleys), vertical farms lower reliance on manual labor, minimize human error, and stabilize operational costs.

Process efficiency

Automation/robotics technologies generate efficiency gains in VF: reducing waste and rework, smoothing throughput, boosting crop yields, heightening product consistency, facilitating production scaling. Such systems also optimize space utilization in dense, multi-story vertical structures, as shuttle robots reposition plants between different stations in the cultivation chain.

Environmental control

Integrated with cameras and IoT-enabled sensors, automation/robotics systems enable continuous monitoring and control of temperature, humidity, CO2, light intensity, moisture levels, and other environmental conditions. They also permit capture and analysis of data streams that facilitate adjustment of production schedules, modification of nutrient profiles, and detection of diseases and other anomalies (Beh, 2022; Kunwar, 2025; Shen et al., 2024).

The detailed study by Kabir et al. (2023) describes the technical features of automated vertical farms across the globe: e.g., Badia Farms (UAE, computer-linked controls of irrigation and feeding), Eagle Technologies (United States, automated seeding, watering, fertilizing), IFarm (Finland, automatic mixing of nutrition blends), Itoh Denki (Japan, underground automated plant factory), Organifarms (Germany, automated berry picking), Seasony (Denmark, integrated AI and autonomous robots to manage vertical farm logistics).

The foremost challenge to commercial adoption of automation and robotics in VF is the capital intensity of these technologies, whose high costs may surpass their efficiency gains. A case in point is Iron Ox, a Silicon Valley-based startup company that developed a system comprising autonomous robots with advanced sensors maneuvering around hydroponic pods. Unable to meet the expectations of venture capitalists who invested nearly $100 million in the company, Iron Ox was liquidated in 2023.

Digital technology

Advances in digital technology have expanded the technological frontier of VF, heightening the power of established technologies in lighting, automation, and robotics.

Networks of IoT-enabled sensors enable real-time measurement of environmental conditions, water and energy consumption, plant health, and crop growth metrics. Through cloud services, dashboards, and mobile applications, VF companies can remotely monitor information streams and calibrate facility operations with feedback loops. Big data analysis permits aggregation of historical and real-time data to identify patterns in plant growth and resource use, promoting continuous improvement in VF operations. AI platforms create optimal nutrient recipes, forecasts of resource needs, and predictive algorithms to maximize crop yields and plant quality. Machine learning models reduce energy costs by adjusting equipment settings based on sensor data (Kaya, 2025; Luo et al., 2023; Rathor et al., 2024).

Kabir et al. (2023) catalogs uses of AI algorithms in the industry: e.g., ANN (Artificial Neural Network) for growth prediction; CNN (Convolutional Neural Network) for disease detection and identification; MLP (Multilayer Perception) for phenotyping; WGAN (Wasserstein Generative Adversarial Network) for assessment of plant stress. The authors note that small and medium vertical farms may lack the human and technical resources needed to train and deploy AI models. They also cite concerns about privacy and security of sensitive data used in AI applications.

Kaya (2025) provides a survey of industry use cases that indicate favorable results of applications of AI for energy management, lighting use, temperature control, humidity regulation, nutrient delivery, and CO2 enrichment. The author notes that scaling of such applications from pilot to commercial deployment presents major technical challenges. Moreover, the integration of AI software, smart sensors, and automation systems entails significant upfront capital investments that may impede commercial adoption by small and medium companies.

Fei et al. (2025) reports applications of AI, IoT, big data, and blockchain in UPA (Urban and Peri-Urban Agriculture). UPA is an approach to food production, processing, and distribution within and on the outskirts of large metropolitan cities that shortens supply chains, enhances food security, and reduces dependence on food imports. The authors cite the experience of Singapore, where vertical farming is the central component of the city's "30 by 30" program to boost the local agri-food industry. But one of Singapore's pioneering vertical farms (Sky Greens) has scaled back operations, illustrating the financial pressures stemming from the high capital costs and operating expenses of high-tech urban farming.

Materials and methods

We conducted a survey of VF companies globally. The survey prompted respondents to assess levels of technology adoption in the following domains:

- Advanced Lighting
- Automation and Robotics
- Advanced Sensing
- Artificial Intelligence
- Water Recycling and Filtration
- Growing Media and Inputs

Within each of the above-named technology domains, we asked respondents to evaluate adoption of specific technologies (e.g., Automated Nutrient and Water Delivery within Automatic and Robotics; Artificial Neural Networks within Artificial Intelligence; Infrared Carbon Dioxide Sensors within Advanced Sensors).

The survey questions prompted the VF company respondents to gauge the level of technology adoption along an ordinal five-point scale:

- Fully Adopted: Technology integrated into standard organizational processes
- Partially Adopted: Technology in implementation stage
- Started Adoption: Technology in pilot or provisional stage
- Actively Considering: Technology in decision stage
- Not Considering: Technology rejected

Prior to distribution, we tested the survey with the Chief Technology Officer of a leading VF company. That test validated the survey as an effective instrument to assess levels of technology adoption by VF companies.

All data collection took place in 2025. Using industry association reports (American Association for Urban and Vertical Farming, Association for Vertical Farming), we assembled a global list of 235 VF companies. We verified the commercial status of the listed companies via Crunchbase and PitchBook. The list covered a broad range of VF companies across the major technology systems used in the industry: hydroponics (representing 60 percent market share), aeroponics (the fastest growing segment), and aquaponics (a niche market that integrates fish farming and plant cultivation) (Mordor Intelligence, 2025).

We cleansed the list down to 90 firms by limiting the survey to commercially active companies primarily engaged in VF operations. The survey excluded bankrupt and insolvent VF companies, businesses engaged in other forms of non-conventional farming (e.g., greenhouses, container farming), and enterprises specializing in production and distribution of vertical farming equipment. The target list comprised VF companies headquartered in Asia, Europe, and North America, along with a smaller number of firms based in Latin America and Middle East/Africa. The survey thus captured second-wave firms by design: commercially active companies that navigated or avoided the industry contraction. Bankrupt and insolvent firms were excluded as no longer operational.

The survey generated 9 valid responses yielding a response rate of 10%. We counted survey responses as valid if the respondent completed all of the questions and represented an operationally active VF company (i.e., not a bankrupt or insolvent firm or an equipment manufacturer). The respondents came from a wide range of countries: Australia, Hong Kong, Germany, Netherlands, Sweden, United Arab Emirates, United Kingdom, and the United States. Most of the responding companies utilized hydroponic systems, reflecting that segment's standing as the current industry leader. However, the responding group included a VF company anchored to aeroponics, the industry's fastest growing segment whose technological requirements offer important contrasts with hydroponic systems that we address in the paper.

5 of the 9 responding VF companies agreed to one-hour follow-up interviews, which we conducted via Zoom. In these interviews, we prompted the participants to elaborate on their survey responses, focusing on the business factors driving technology adoption decisions. We recorded and transcribed each of the interviews, checking the responses of the interviewees against the results of the online survey. All of the interviewees held senior leadership positions (Chief Executive Officer or Chief Technology Officer) at their companies.

From the interview group, we selected three companies as full case studies to present in this article: SweGreen, LettUs Grow, Vertical Harvest. We applied the following criteria in this selection: achievement of profitable growth; clearly articulated technology strategy; and willingness divulge details on the company's operations and competitive positioning. The selected companies represented variations in geography (Sweden, United Kingdom, United States), business models (farming-as-a-service, technology licensing, social enterprise), and VF technology platforms (hydroponics, aeroponics). These in-depth case studies illustrate the trade-offs between technology, organization, and environment.

The case studies were prepared using a uniform structure of Background and Technology Adoption, disaggregated into specific categories within the six technology domains. Company materials such as websites were used to augment the surveys and interviews as needed.

Results

The research literature reviewed above features detailed studies of commercial applications of advanced technologies in the VF industry, drawing on theoretical models, laboratory experiments, and field tests. However, the extant literature leaves unanswered the question of how business factors (competitive, financial, operational, strategic) shape corporate decisions on technology adoption.

Our survey of technology adoption by VF companies addresses that question. The aggregate results of the company survey are reported in Figures 1–6 below. Our interpretation of these results is provided in the Discussion section of the paper in the context of the TOE framework.

Advanced lighting technologies

All of the survey respondents (9 of 9) have either fully adopted or started adoption of LED lighting. This result echoes the preceding literature review showing that the operational advantages of LEDs in vertical farms (low heat, high energy efficiency, long performance lifetime) have made this lighting technology the prevailing production standard in the VF industry. Most of the respondents (6 of 9) reported implementation of color mixing, a technology that improves the ability of vertical farms to calibrate and customize light intensity levels and wavelengths to optimize cultivation of specific crop species (Figure 1).

Optical fiber daylighting is an interesting and promising technology that enables VF companies to channel natural sunlight into interior structures, augmenting LED systems and reducing energy costs. But most of our survey respondents (7 of 9) are not considering adoption of that technology.

Automation and robotics technologies

The survey question on company adoption of automation and robotics technologies yielded varied approaches. As expected, most respondents reported full or partial adoption of real-time monitoring (8 of 9) and automated nutrient and delivery systems (9 of 9), whose integration with IoT-enabled sensors and other technologies strengthens the business case for their deployment (Figure 2).

The survey shows comparatively low adoption rates of more advanced technologies such as automated transplanting (1 of 9), automated harvesting (2 of 9), robotic packaging (2 of 9), and fully autonomous unmanned VF (4 of 9).

Advanced sensing technologies

Most survey respondents reported full or partial deployment of nutrient sensing (7 of 9), optical sensing (5 of 9), and integrated sensing for precision agriculture (5 of 9). These sensing systems permit continuous tracking of temperature, humidity, air quality, irrigation, nutrients, and plant health. Most of the survey participants (8 of 9) are planning or beginning adoption of spectral sensors, which measure how plants interact with light to facilitate calibration of spectra and wavelengths. Some respondents are implementing NICDS (Infrared Carbon Dioxide Sensors), which permit continuous monitoring and control of CO2 levels to maximize plant photosynthesis while protecting the safety of facility operators (4 of 9) (Figure 3).

The survey showed the following trends in other technologies in the advanced sensing group. Most of the respondents are in early-stage

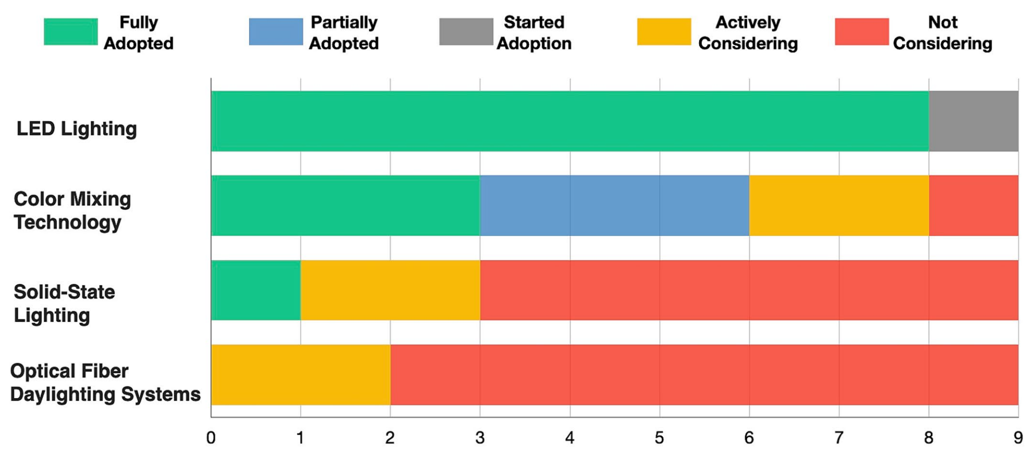

FIGURE 1
To what degree has your company adopted the following advanced lighting technologies?

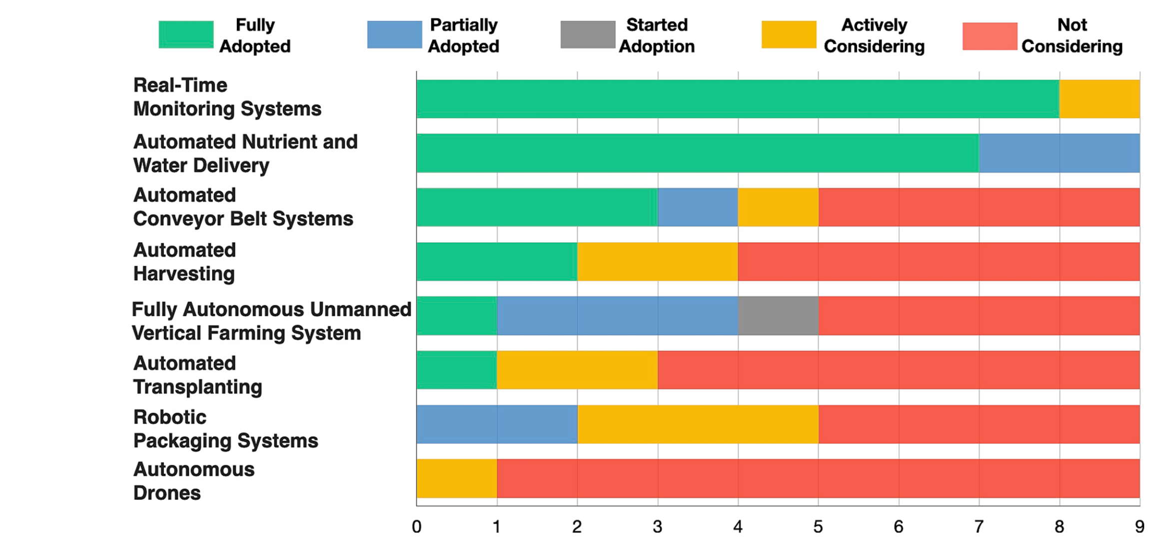

FIGURE 2
To what degree has your company adopted the following automation and robotics technologies?

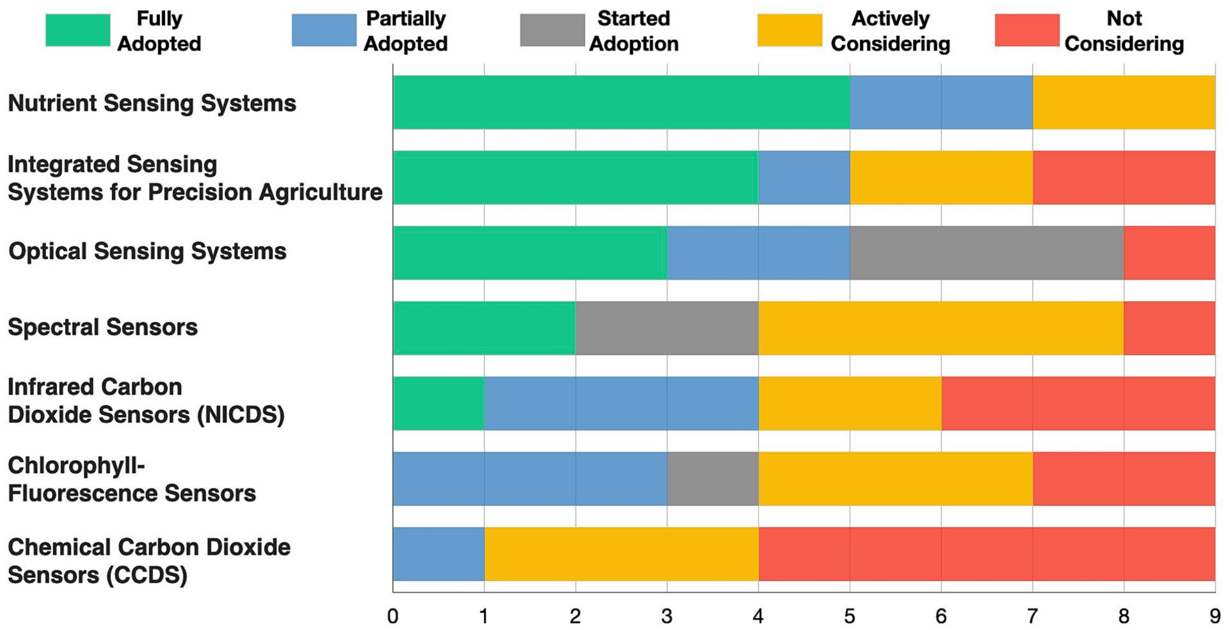

FIGURE 3
To what degree has your company adopted the following advanced sensing technologies?

adoption of chlorophyll-fluorescence sensors (7 of 9), which monitor photosynthetic efficiency in real time.

Adoption rates are lower for CCDS (Chemical Carbon Dioxide Sensors), which measure CO2 levels via electrochemical means but offer few advantages over infrared-based NICDS systems (1 of 9).

Artificial intelligence technologies

We prompted survey participants to assess technology adoption in six categories of Artificial Intelligence: ANN (Artificial Neural Network), DNN (Deep Neural Network), DKL (Deep Kernel Network), MSAM (Multivariate Standard Addition Method), GLCM (Gray Level Co-Occurrence Matrix), and CNN (Convolutional Neural Network).

The AI survey yielded bifurcated results. Nearly half of the surveyed companies (4 of 9) have either adopted or were actively considering adoption of all six AI technology types. The other respondents were not considering any investments in Artificial Intelligence (Figure 4).

Water recycling and filtration technologies

The survey on water recycling and filtration technologies yielded the following results. A majority of respondents (6 of 9) have fully adopted NFT (Nutrient Film Techniques), which utilize

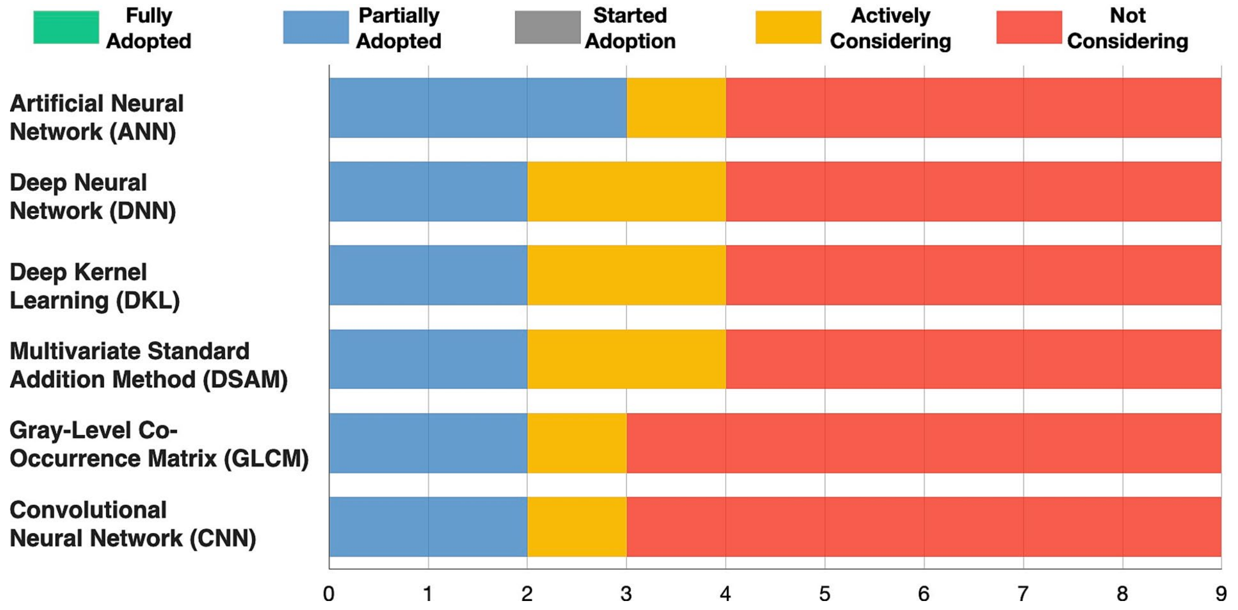

FIGURE 4
To what degree has your company adopted the following artificial intelligence technologies?

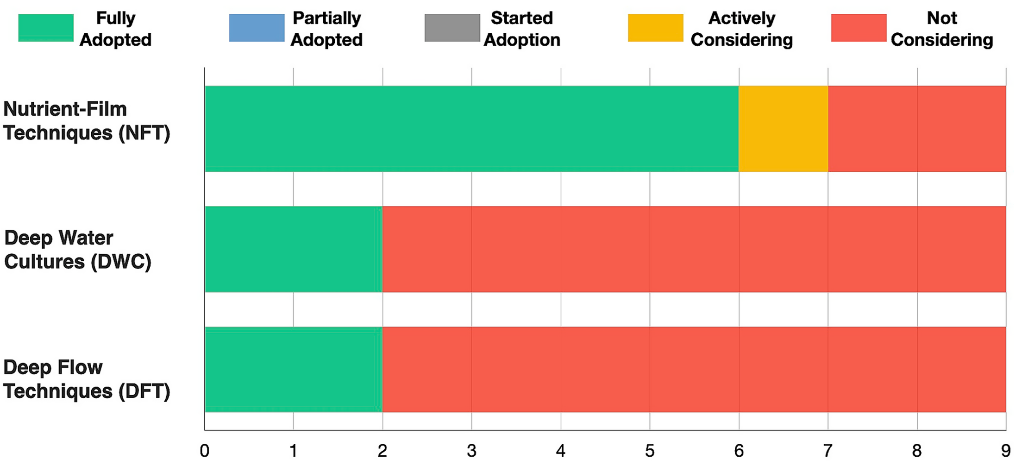

FIGURE 5
To what degree has your company adopted the following water recycling and filtration technologies?

multi-tier channel racks to recirculate nutrient solutions around plant roots.

The survey showed lower rates of adoption of other water-related technologies. A majority of respondents (7 of 9) are not considering DWC (Deep Water Cultures) or DFT (Deep Flow Techniques) (Figure 5).

Growing media and inputs

The survey on growing media and inputs showed full adoption (9 of 9) of soilless media across the entire sample. Most respondents (6 of 9) also reported full adoption of synthetic inputs and synthetic growing media. They indicated lower rates of adoption of organic growing media and inputs.

Most of the survey respondents (6 of 9) indicated no intention to adopt GMOs (Genetically Modified Organisms), reflecting controversies over the safety of GMO-derived food products and their unpopularity in Europe and other regions (Figure 6).

Company case studies

Leaders of VF companies who participated in the online survey conducted Zoom interviews with the authors in winter 2025. During those interviews, we asked a series of questions prompting the participants to elaborate on their responses to the online survey. The interviews form the basis of the case studies detailed below.

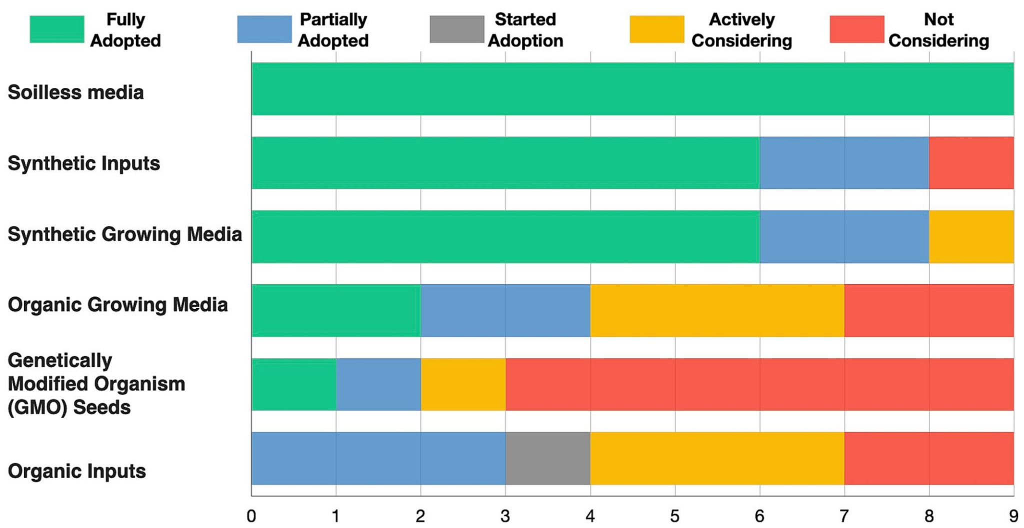

FIGURE 6
To what degree has your company adopted the following growing media and inputs?

Case study #1: SweGreen

Background

Stockholm-based SweGreen is the successor to Plantagon, an early mover in VF founded in 2008. Funded by the Swedish government and private investors, Plantagon built a portfolio of technology patents, launched Stockholm's first commercial VF facility, and broke ground on a $40 million, 17-story green skyscraper (dubbed "World Food Building") in Linköping in southern Sweden. But cashflow problems forced the company to declare bankruptcy in February 2019.

Leveraging Plantagon's technological initiatives and drawing on the lessons of that company's demise, the founders of SweGreen developed an FaaS (Farming-as-a-Service) business model. Through this model, SweGreen installed modular farming units inside grocery stores, restaurants, hotels, and other commercial establishments. Combining advanced hydroponic technology, IoT sensors, and AI-based cloud computing, SweGreen remotely monitors in-store farm operations (lighting, temperature, humidity, water, nutrient delivery) to maximize plant growth, optimize product quality, and calibrate production to market demand and seasonal trends. The company's closed-loop system promotes water conservation, recycling of inputs, and minimization of waste.

These features enabled SweGreen to realize operational efficiencies that eluded Plantagon, whose business model prioritized the development of costly VF systems that were misaligned with the competitive dynamics of the retail food market.

Under the FaaS model, SweGreen retains ownership of in-store farming units, generating revenue through user subscription fees–a financial structure that mitigates the cashflow challenges that plagued Plantagon and other VF companies that deployed expensive technologies to sell fresh produce in commodity markets. Additionally, the visual allure of SweGreen's in-store production model enhances the customer experience, conferring a competitive advantage over rival companies anchored to tiered distribution.

SweGreen deploys two in-store production systems: Freja (a large-scale unit with a capacity of 300 crops per day) and Saga (a small-scale unit producing 68–116 crops per day). The company's product offerings include lettuce, basil, dill, coriander, mint, parsley, oakleaf, and thyme. SweGreen operates farming units in several ICA supermarkets (Sweden's largest grocery retailer), coops, and restaurants as well as Mälardalens University in Västeras. The company also operates in-store facilities in Berlin and Munich and is pursuing growth opportunities in other German cities.

SweGreen's technology strategy illustrates the determination of company founders to avoid the mistakes made by firms like Plantagon–first generation VC-funded vertical farming companies whose heavy capital expenditures hindered their ability to compete in highly competitive, low-margin commodity markets. SweGreen's selective approach to technology adoption (prioritizing technologies that create business value and generate operational efficiencies) lowers the company's VC reliance ($8.5 million VC funding compared to $315 million raised by New Jersey-based AeroFarms, which entered bankruptcy in 2023).

SweGreen's technology strategy also differentiates the company from other industry players that utilize in-store farming units. SweGreen's FaaS model employs modular production units in geographically dispersed stores linked with cloud-based remote monitoring of environmental conditions, seeding, planting, harvesting, and nutrient delivery. This distributed system engages customer staff as active participants in food production, raising the skill sets of store employees and minimizing the need for on-site intervention by SweGreen engineers. SweGreen supplies customers with seeds, substrates, and other inputs. But the food production process takes place entirely within the client stores. By contrast, Berlin-based InFarm (once Europe's largest VF company) developed an in-store business model that relied on centralized cultivation of pre-grown seedlings, raising operational and logistical costs that led to the company's declaration of insolvency in 2023.

Technology adoption

Automation and robotics

Figure 7 summarizes SweGreen's responses to the technology survey. SweGreen's approach to automation and robotics demonstrates the company's efforts to align technology adoption with real-world business needs. Following the broad pattern shown in the company survey, SweGreen has fully adopted automated nutrient and water delivery and real-time monitoring. To support its FaaS model, the company has partially adopted autonomous unmanned VF technology and automated conveyer belt systems.

However, SweGreen's in-store model (covering the full production cycle from seeding to harvesting) obviated the need for automated transplanting and robotic packaging. Some companies (notably UAE-based IFarm) are developing autonomous drones, which are technically feasible in large-scale indoor farms with high vertical stacks. But the compact modular design of SweGreen's Freja and Saga platforms ruled out deployment of in-store drones.

Lighting

SweGreen has fully adopted LED lighting, which has become a standard in the VF industry. Heightening the value proposition of SweGreen's FaaS offering, the company captures the heat emitted by LED lighting to heat grocery stores. The company has also fully adopted color-mixing technology, which promotes photosynthesis by calibrating the light spectrum to individual plant species.

SweGreen reported that it was not intending to adopt optical fiber daylighting systems, since this is an expensive technology misaligned with SweGreen's in-store modular farming units.

Water recycling/filtration

Like other VF companies that employ hydroponics (e.g., 80 Acres), SweGreen has fully adopted Nutrient Film Techniques in which plant roots are suspended in shallow sloped channels that enable continuous flow of water and nutrients. The nutrient solution is then collected and recirculated, providing a closed-loop system that conserves water and optimizes space utilization. SweGreen's NFT-based system includes a condensation device that captures water vapor released by plants. The company has opted not to deploy Deep Flow Techniques or Deep Water Cultures, which require greater space and more water than the thin-stream NFT system.

Growing media and inputs

SweGreen's responses in this technology category generally align with the overall survey results, showing full or partial adoption of soilless media and synthetic inputs. In SweGreen's hydroponic system, crops are seeded, germinated, and cultivated in stone wool, a light-weight, inorganic fibrous material that provides high water retention and airflow to plants. Like other companies in the survey, SweGreen has not adopted GMOs, which are unpopular with consumers and heavily regulated in Sweden and other European Union countries.

Sensing technologies

Reflecting the FaaS model requirements of remote monitoring of in-store farming units, SweGreen has undertaken larger investments in advanced sensing technology than other companies in the survey. IoT-enabled sensors permit analysis, storage, and real-time monitoring of key environmental metrics (temperature, humidity, light intensity, moisture conditions, pH levels) to optimize plant growth and health. Nutrient sensors enable continuous, precise measurement of nutrient concentrations in recycled solutions, a critical factor in closed-loop hydroponic systems like SweGreen's Freja and Saga platforms.

In addition to full adoption of nutrient sensing and integrated sensing systems, SweGreen has partially adopted Infrared Carbon Dioxide Sensors (monitoring of CO_2 levels) and Chlorophyll Fluorescence Sensors (monitoring of plant stress). The company has begun implementation of Optical Sensors (monitoring of plant density, size, ripeness, and disease symptoms) and Spectral Sensors

Automation & Robotics | Lighting | Artificial Intelligence | Sensing Technologies | Water Recycling/ Filtration | Growing Media & Inputs

Fully Adopted	Partially Adopted	Started Adoption	Actively Considering	Not Considering
Automated Nutrient & Water Delivery	Fully autonomous unmanned vertical farming	Optical Sensing System	Deep Neural Network	Automated Transplanting
Real-Time Monitoring System	Automated Conveyer Belt System	Spectral Sensors	Deep Kernel Learning	Automated Harvesting
LED Lighting	Artificial Neural Network		Multivariate Standard Addition Method	Autonomous Drones
Color-Mixing Technology	Infrared Carbon Dioxide Sensors			Robotic Packaging System
Nutrient Sensing System	Chlorophyll Fluorescence Sensors			Solid State Lighting
Integrated Sensing for Precision Agriculture	Organic Inputs			Optical Fiber Daylighting
Nutrient-Film Techniques	Synthetic Inputs			Gray-Level Co-Occurrence Matrix
Soilless Media				Convolutional Neural Network
Synthetic Growing Media				Chemical Carbon Dioxide Sensors
				Deep Water Cultures
				Deep Flow Techniques
				Organic Growing Media
				Genetically Modified Organism Seeds

FIGURE 7
Below summarizes SweGreen's responses to the technology adoption survey.

(enabling calibration and adjustment of LED lighting to promote plant photosynthesis).

Artificial intelligence

SweGreen has also moved more aggressively than other surveyed companies in applications of AI, which strengthens the company's capacity to analyze the large quantities of data generated by in-store sensors. The company's expanding AI portfolio includes Artificial Neural Network (disease detection, resource optimization, predictive analytics), Deep Neural Network (plant health, yield prediction, growth analytics), Deep Kernel Learning (decision support, nutrition management, cloud integration), and Multivariate Standard Addition Method (optimization of nutrient delivery in closed-loop hydroponic systems).

Case study #2: LettUs grow

Background

UK-based LettUs Grow is an aeroponic technology company founded in 2015. The company founders combined expertise in engineering, plant science, and systems design with a desire to minimize food waste. Their first concept was a small, at-home aeroponic kit to enable customers to replace bagged salad products through home-growing. However, they quickly recognized that the opportunity for food system-wide impact was bigger in industrial-scale solutions leveraging their core strengths in high-tech engineering and plant science. LettUs Grow's pivot from a direct-to-consumer to business-to-business sales model allowed the company to scale from a modular at-home aeroponics kits to 40-foot container farms.

The core of LettUs Grow's value proposition is the company's patented ultrasonic aeroponic technology, which was engineered to overcome a critical challenge in conventional aeroponics. While aeroponic systems (which apply nutrient mist on airborne plant roots) offer superior root oxygen access and faster growth than hydroponics, their commercial adoption has been hindered by traditional high-pressure nozzles that are prone to clogging from mineral salt buildup, making them unreliable and high maintenance for large-scale operations.

LettUs Grow's aeroponic system replaces clog-prone nozzles with ultrasonic atomizers. These devices use high-frequency sound waves to vibrate nutrient solution into a fine, consistent fog, eliminating the primary point of failure in conventional systems. This nozzle-free design makes LettUs Grow's aeroponic systems reliable and commercially viable at an industrial scale.

In-house and partnered research demonstrate that LettUs Grow's aeroponic system boosted crop growth rates by over 70%. By solving this engineering bottleneck, LettUs Grow transformed a high-potential cultivation method into a scalable industrial production strategy supported by advanced technology.

LettUs Grow's first commercial product was Drop & Grow, a closed-loop aeroponic system within a shipping container. This "farm-in-a-box" solution responded directly to the market's initial enthusiasm for turn-key systems, allowing LettUs Grow to generate early revenue and validate its product-market fit.

LettUs Grow then executed a strategic pivot by transitioning from selling high-capital hardware products to a scalable, capital-light business model focused on technology licensing and component supply. The new core offering became the Aeroponic Rolling Benches, a modular irrigation system designed for retrofitting into existing greenhouse operations that employs LettUs Grow's proprietary ultrasonics nutrient delivery and mobile power distribution technologies. This shift allowed the company to target a larger market of established commercial growers seeking high-value components rather than off-the-shelf solutions, aligning its business model with the needs of a more mature VF market.

Furthering the company's strategic refocus and narrowing of product offerings, LettUs Grow spun out its farm management software (Ostara) into a separate company. This allowed LettUs Grow to concentrate on its core competency in aeroponic hardware components, bolstering the company's positioning as a specialized physical technology provider. This move also enabled the Ostara team to pursue a pure SaaS (Software-as-a-Service) model that served the vertical farming market more broadly and independently of LettUs Grow's specialized aeroponic equipment.

Technology adoption

Lighting

Figure 8 summarizes LettUs Grow's responses to the technology survey. LettUs Grow has fully adopted LED lighting and partially implemented color-mixing technologies. The company has not considered solid state lighting or optical fiber daylighting systems, whose commercial value to LettUs Grow is uncertain.

Sensing technologies

Real-time monitoring technologies are a key component of effective aeroponic hardware systems. LettUs Grow relied on electro-conductivity and pH monitoring for nutrient dosing adjustments and timing. While real-time, in-loop nutrient analysis is currently limited, LettUs Grow has explored new technologies like mass spectrometry that would enable the company to integrate real-time sensing data into nutrient delivery management.

Water recycling and filtration

VF systems use much less water than soil-based agriculture. Within the VF domain, aeroponic systems (in which water is misted on plants) require significantly less water than hydroponics (in which plant roots are continuously submerged).

LettUs Grow filtered the water drained from plants, then UV sterilized the water for reuse. This method of water filtration and recycling enabled LettUs Grow to avoid recirculating pest and disease contamination. While company leaders have not contemplated adoption of Deep Water Culture or Deep Flow Techniques (both of which are more relevant to hydroponics than aeroponics), they have considered Nutrient Film Techniques, adapted for application of continuous nutrient flows across plant roots in aeroponic systems.

Artificial intelligence

Since LettUs Grow has focused on hardware development to support its advanced aeroponic system, the company has not yet adopted AI. However, the company has designed its aeroponic hardware for operability with AI-powered software programs. Meanwhile, LettUs Grow has deployed fully automated nutrient and water delivery

Automation & Robotics | Lighting | Artificial Intelligence | Sensing Technologies | Water Recycling/ Filtration | Growing Media & Inputs

Fully Adopted	Partially Adopted	Started Adoption	Actively Considering	Not Considering
Automated Nutrient & Water Delivery	Color-Mixing Technology		Spectral Sensors	Fully autonomous unmanned vertical farming
Real-Time Monitoring System	Nutrient Sensing System		Chlorophyll Fluorescence Sensors	Automated Transplanting
LED Lighting	Optical Sensing Systems		Integrated Sensing for Precision Agriculture	Automated Harvesting
Soilless Media	Synthetic Growing Media		Nutrient-Film Techniques	Autonomous Drones
Synthetic Inputs			Organic Growing Media	Robotic Packaging Systems
			Organic Inputs	Solid State Lighting
				Optical Fiber Daylighting
				Artificial Neural Network
				Deep Neural Network
				Deep Kernel Learning
				Convolutional Neural Network
				Gray-Level Co-Occurrence Matrix
				Multivariate Standard Addition Method
				Chemical Carbon Dioxide Sensors
				Infrared Carbon Dioxide Sensors
				Deep Water Cultures
				Deep Flow Techniques
				Genetically Modified Organism Seeds

FIGURE 8
Below summarizes LettUs Grow's responses to the technology adoption survey.

systems and corresponding integrated monitoring systems to maximize nutrient delivery for plant health.

Growing media and inputs

Growing media use in an aeroponic system was minimal. LettUs Grow used a small amount of synthetic, non-GMO growing media with PLA-based binders to ensure germination and early establishment of plants.

The company has considered adoption of organic certified growing media and inputs. But organic fertilizers were challenging to employ in aeroponic systems, as they contained particulates that clogged water misting equipment and caused varied nutrient delivery to individual plants.

Case study #3: vertical harvest

Background

As a hydroponic VF company, U.S.-based Vertical Harvest faced different financial, operational, and technological challenges than LettUs Grow and other indoor farms that employ aeroponics. Hydroponic systems afford lower setup and maintenance costs, lower dependence on specialized equipment, less mechanical complexity, and more reliable yields than aeroponics-based facilities. Hydroponic systems also permit indoor cultivation of a wider variety of crops, including vine and fruit products. However, hydroponic systems are less water-efficient than aeroponics, requiring 2–3 times more water per cycle.

Vertical Harvest operates two facilities in the United States, the first of which opened in 2016 in Jackson, Wyoming in the western U.S. The second facility in Westbrook, Maine on the U.S. east coast covers 52,000 square feet with annual capacity of 2.5 million pounds of fresh produce. Vertical Harvest's fully enclosed facilities enable year-round production of leafy greens and micro-greens in the two weather-challenged states.

Vertical Harvest operates as a for-profit company committed to positive social impact in food accessibility, environmentalism, and labor relations. Vertical Harvest has developed a unique employment model focusing on disability inclusion. Recognizing high unemployment rates within the disability community, company leaders prioritized inclusivity (including worker-friendly design and employee training) for employees with mental and physical disabilities.

As detailed below, Vertical Harvest's commitment to labor force inclusivity shaped the company's technology adoption strategy-- notably investments in machinery equipment that allowed it to broaden the range of employable local workers.

Technology adoption

Lighting

Figure 9 summarizes Vertical Harvest's responses to the technology survey. Vertical Harvest is committed to energy efficiency in its operations, driving decisions on technology and equipment at every stage of production. To that end, the company has fully adopted energy-efficient LED lighting. But with 40,000 fixtures in the VF facility, LED lighting remains the foremost driver of energy costs at Vertical Harvest.

To reduce energy costs, Vertical Harvest installed a 1.5 megawatt lighting system, sufficient to run at 50–60 percent capacity with uniform lighting across the facility. To minimize electricity consumption at peak rate times, the company turns the lights off during daylight hours and turns them on at night. To reduce heat load on plants, Vertical Harvest installed a mechanism to divert LED-generated heat away from the growth room, along with an air recirculation system that captures moisture for plant irrigation.

Automation & Robotics | Lighting | Artificial Intelligence | Sensing Technologies | Water Recycling/ Filtration | Growing Media & Inputs

Fully Adopted	Partially Adopted	Started Adoption	Actively Considering	Not Considering
Automated Nutrient & Water Delivery	Robotic Packaging Systems	Optical Sensing Systems	Color-Mixing Technology	Autonomous Drones
Real-Time Monitoring System	Fully Autonomous Unmanned Vertical Farming System		Artificial Neural Network	Solid State Lighting
Automated Transplanting	Chlorophyll Fluorescence Sensors		Deep Neural Network	Optical Fiber Daylighting
Automated Harvesting			Deep Kernel Learning	Integrated Sensing for Precision Agriculture
Automated Conveyor Belt Systems			Convolutional Neural Network	Chemical Carbon Dioxide Sensors
LED Lighting			Gray-Level Co-Occurrence Matrix	Infrared Carbon Dioxide Sensors
Nutrient-Film Techniques			Multivariate Standard Addition Method	Deep Water Cultures
Soilless Media	Genetically Modified Organisms		Nutrient Sensing System	Deep Flow Techniques
Synthetic Inputs			Spectral Sensors	Organic Inputs
Synthetic Growing Material				Organic Growing Media

FIGURE 9
Below summarizes Vertical Harvest's responses to the technology adoption survey.

While company leaders have considered color-mixing technology, they determined that a two-color lighting spectrum (red/blue) was sufficient for Vertical Harvest's purposes. Lighting systems with mid-spectrum capabilities provide certain benefits, but boost energy costs to levels that neutralize those advantages.

Automation and robotics

Vertical Harvest's approach to automation and robotics similarly reflects the company's prioritization of operational efficiency in technology adoption decisions. Employing Siemens' Opcenter X digital manufacturing software, the company installed a semi-automated production system at its new VF facility in Maine. Seeds are loaded onto trays, conveyed up to a germination chamber and growing room, then conveyed down for automated harvesting and packaging. Each growing tray is embedded with an RFID tag integrated with the Siemens process tracking software, enabling precise monitoring from seeding to harvesting. This system captures granular data (seed numbers, plant yields) that supports batch-level performance analysis and allows rapid iteration of growing recipes.

Certain elements of Vertical Harvest's production process (e.g., blending) cannot be cost effectively automated. Illustrating the company's measured approach to technology adoption, Vertical Harvest has declined to invest in costly, complex process technologies to perform "last mile" work that is better undertaken by humans.

Reflecting the company's "human first" philosophy, Vertical Harvest's deployment of automation/robotics technologies aims not to replace manual labor, but to raise worker productivity and reduce incidence of injury in high-speed repetitive operations. The company has installed universal design equipment (e.g., adjustable screens) that lower barriers to entry for disabled workers. Labor force reduction has occurred not with manual workers, but with middle managers whose workflow supervisory functions are now automated.

Sensing technologies

Vertical Harvest has employed a variety of sensing technologies to monitor facility performance and plant growth. The company has begun adoption of chlorophyll-fluorescence sensing systems and optical lighting systems to collect data on crop health. The company has actively considered nutrient-sensing systems and spectral sensors, but has not considered NICDS or CCDS.

Leveraging computer vision technology sourced from Stockholm-based Ecobloom, Vertical Harvest has focused on environmental monitoring (air, light, water, time). Low-cost, high-resolution cameras deployed throughout the production facility enable real-time tracking of photosynthetic activity, identifying minute plant changes that cannot be detected by humans. Through this sensing system, the company makes operational adjustments (e.g., recalibrating light intensity) to minimize plant stress and optimize yields.

Water recycling and filtration

As a hydroponic farm, Vertical Harvest faced strong financial pressure to minimize water waste in facility operations. Vertical Harvest has fully adopted NFT, which aids in water recirculation. The company has not considered Deep Water Cultures or Deep Flow Techniques.

Artificial intelligence

At the time of the interview, Vertical Harvest had not yet adopted AI technologies. But company leaders have actively considered investments in AI platforms (ANN, DNN, DKL, DSAM, GLCM, and CNN) at the new Maine facility for recipe optimization and process improvement. The company has centralized operational data in Snowflake (an

AI data cloud service) to support advanced analytics and future machine learning applications.

Growing media and inputs

Vertical Harvest's standing as a hydroponics-based vertical farm drove its decisions on growing media and inputs. The company has fully adopted soilless media, synthetic growing media, and synthetic inputs. Soilless growing media allows the crops to develop in a predictable environment with optimal airflow, while synthetic growing media and inputs boost yields and improve nutrient delivery. The company has not considered organic growing media and organic inputs, which are not compatible with hydroponic farming.

In contrast to non-American VF companies that shun GMO, U.S.-based Vertical Harvest has partially adopted GMO seeds that increase crop growth rates and yields.

Discussion

This study addresses a gap in the VF literature by examining how business considerations shaped technology adoption decisions following the industry meltdown of the early 2020s. Using a global survey, executive interviews, and case studies, we find a consistent pattern: surviving VF companies adopted technologies selectively, prioritizing return on investment and operational fit over technological sophistication. LED lighting and NFT water systems are widely adopted technologies, while automation, robotics, and AI show highly variable adoption driven by firm-specific financial capacity and strategic positioning.

Our study suggests that technology adoption in vertical farming is constrained less by technical feasibility than by market dynamics and operational economics. The high failure rate of first-wave VC-funded vertical farms was mainly attributable to capital-intensive, over-engineered technology strategies misaligned with price-sensitive commodity food markets. Second-wave companies–exemplified by our three in-depth company case studies–demonstrate that durable growth in VF requires subordinating technology decisions to market demand, competitive positioning, and financial discipline. For example, SweGreen's technology adoption decisions prioritized operational efficiency, incorporating lessons from the failure of its predecessor Plantagon.

Figure 10 represents our conceptual synthesis of the factors driving the technology adoption decisions of VF companies that achieved profitable growth following the industry decline. The VF technologies exhibiting the highest adoption intensity generated energy and labor cost savings, operational efficiencies, and other concrete benefits.

For example, Nutrient Film Techniques (NFT) has proven effective for indoor farm production of high-density, fast-growing, shallow-rooted crops such as lettuce, spinach, kale, herbs, micro-greens, and strawberries (Palmitessa et al., 2024). By contrast, Deep Water Cultures (DWC) is best suited for cultivation of large root crops (e.g., cucumbers and tomatoes) in ponds, affording less efficient space utilization than NFT-based systems. Like NFT, DFT (Deep Flow Techniques) uses recirculating water methods. But whereas NFT systems employ lightweight thin channels, DFT systems comprise deep troughs or ponds with higher water volumes and larger footprints (Mullins, 2023).

In the Advanced Sensing Technology domain, the high adoption rate of Nutrient Sensing Systems reflects the ability of VF companies to capitalize on dramatic advances in low-power, ultra-miniaturized, wireless-connected sensors. Over the past 15 years, the unit cost of IoT-enabled sensors has fallen from $1.30 to less than $0.40 (Leonard, 2019). Vertical farms can cost effectively purchase smart sensors in bulk, integrating those devices in their data collection and monitoring networks.

The low adoption rates of other technologies addressed in the study illustrate the reluctance of second-wave VF companies to invest in advanced technologies with uncertain returns. Notwithstanding their potential advantages over electrically power LEDs, Optical Fiber

High Adoption Technologies	Capabilities	Business Outcomes
LED Lighting	• Increased plant growth • Heightened energy efficiency • Integration with color mixing	• Greater yield per square meter • Lower energy costs per square meter • Higher pricing via increased product consistency
Real-Time Monitoring Systems	• Tracking of environmental metrics • Measurement of nutrient concentrations • Storage and analysis of data	• Reduced labor costs • Fewer crop losses • Faster response to operational problems
Automated Nutrient & Water Delivery	• Conservation of water and nutrients • Optimization of water/nutrient delivery • Enabling continuous operations	• Lower operating costs • Higher production throughput • More annual crop cycles
Nutrient Sensing Systems	• Faster plant growth • Continuous tracking of nutrient levels • Precise measurement of nutrient concentrations	• Reduced nutrient waste • Tighter cost control • Lower operational complexity
Nutrient Film Techniques	• Water conservation • Nutrient recirculation • Optimization of closed-loop systems	• Higher yields per unit of water • Improved utilization of space • Improved unit economics for high-density crops
Soilless Media	• Increased water retention • Heightened airflow and oxygen availability • Precise nutrient management	• Lower risk of soil-borne diseases • More predictable production flows • Increased shelf-life of produce
Synthetic Inputs	• Precise, predictable, replicable formulations • Rapid correction of nutrient deficiencies • Management of pH levels	• Increased yields • Lower nutritional variability • Easier scaling of production
Artificial Neural Network	• Disease detection • Predictive analytics • Nutrient recipes	• Better demand and yield forecasting • Increased resource utilization • Higher profit margins

FIGURE 10
Below represents our conceptual synthesis of the factors driving the technology adoption decisions of VF companies that achieved profitable growth following the industry decline.

Daylighting Systems raise a number of financial and operational challenges: high equipment costs (sun tracking, collection, and concentration devices); solar variability; transmission losses; mechanical complexity (Sharma, 2025). The declining cost and rising quality of LEDs further weaken the business case for investments in optical fiber daylighting.

Within the AI domain, 6 specific AI categories were used in the survey. 2 of 9 firms had partially adopted all of the AI technology categories. The majority of companies (5 of 9) were not even considering any of the AI technology categories. Specifically, Artificial Neural Networks (ANN) had the highest adoption rate (3 of 9 partially adopted, 1 actively considering). ANN enables prediction and control of lighting and water requirements, vision-based detection of plant disease and stress, and modeling of nutrient recipes.

The other 5 AI technologies had low adoption rates: Deep Neural Network (which creates computer vision models for plant counting, growth stage classification, and evaluation of leaf color/texture), Deep Kernel Network (which supports the development of digital twins and probabilistic models for optimization of VF operations), Multivariate Standard Addition Method (which enables real-time analysis of nutrient solutions used in aeroponic and hydroponic farms), Gray Level Co-Occurrence Matrix (which supports computer vision systems that track changes in leaf surface patterns), and Convolutional Neural Network (which supports vision-based VF automation including crop monitoring, robotics harvesting, and climate/ irrigation control) (Natarajan et al., 2024; Sujatha et al., 2025).

Among the three companies featured in the case studies, Case #1, SweGreen has moved most aggressively in AI adoption. This result illustrates the complementarities between AI and SweGreen's FaaS model, which enables the remote capture and analysis of in-store environmental data (lighting, temperature, humidity) to optimize production and monitor plant health. Case #3, Vertical Harvest began exploration of AI for the company's new production facility in the state of Maine. Case #2, LettUs Grow had no plans to use AI.

AI innovation was moving quickly at the time of this study's 2025 data collection, with some of the AI categories benefitting from rapid LLM advances. Nevertheless, AI adoption was still stymied by the high costs of AI licenses and technical support, training of models, and computational/ infrastructural demands (Kaya, 2025; Fei et al., 2025).

Technological–organizational–environmental framework

The three TOE factors (Tornatzky and Fleischer, 1990) frame the central findings of the study (Table 1).

The technological context explains adoption patterns, notably wide implementation of LED lighting and NFT water systems (8 of 9 and 6 of 9 respondents respectively). These technologies became prevailing production standards in the VF industry because of their relative advantages, declining costs, and operational compatibility. From a TOE perspective, the technological context favored LED adoption because of declining costs, operational reliability, and compatibility with existing VF systems.

The organizational context explains firm-level variation in adoption, where each company pivoted to unique business models: SweGreen's Farming-as-a-Service model prioritized investment in sensing and AI, while LettUs Grow's positioning in aeroponics shaped an entirely different adoption profile. Vertical Harvest's social enterprise model (emphasizing labor force inclusion) underpinned the company's adoption of automation/robotics technology that raised productivity and worker safety.

TABLE 1 Summary: technological-organizational-environmental factors.

TOE factor	Evidence from data
Technological	LEDs and NFT widely adopted because of operational reliability, declining costs, compatibility
Organizational	Business models drove adoption patterns (SweGreen FaaS, LettUs Grow technology licensing; Vertical Harvest social enterprise)
Environmental	VC contraction, labor costs, commodity pricing pressures pushed firms toward stronger ROI-focused adoption

The environmental context helps to explain the industry's generational shift: the VC funding collapse and the failure of over-capitalized first-wave firms created pressure that rewarded ROI-driven technology strategies and penalized capital-intensive, market-misaligned ones. The environmental context appears to have exerted strong influence on strategic configurations in the other two sides of the triad: the technology and the organization.

The contrast between first- and second-wave VF firms illuminates the environmental context in TOE terms. First-wave companies such as Plenty, AeroFarms, and IronOx pursued full-stack, capital-intensive technology strategies (autonomous robotics, proprietary AI platforms, large-format facilities) at a moment when venture capital rewarded technological ambition over operational discipline. The environmental shift after 2022 (capital scarcity, commodity price pressure, investor skepticism) rendered those strategies unviable. As our survey and case studies illustrate, second-wave survivors responded by subordinating technology selection to ROI, operational fit, and business model requirements.

Our three case studies demonstrate how the business models and operational platforms of VF companies influence technology adoption decisions. SweGreen's Farming-as-a-Service model–which entails remote monitoring of geographically dispersed in-store production units–led to a heavier reliance on advanced sensors and artificial intelligence than other companies in the survey. LettUs Grow's deployment of aeroponics prompted company leaders to adopt an innovative nozzle technology to mitigate the clogging problem characteristic of aeroponics systems. By contrast, Vertical Harvest's use of water-intensive hydroponics spurred it to invest in water-conserving technologies, specifically Nutrient Film Techniques and Automated Nutrient and Water Delivery.

Our study also illustrates the interplay of technologies in second-wave VF companies. For example, the integration of LEDs, IoT-enabled sensors, and automation/robotics enables VF companies to boost operational efficiency, monitor environmental conditions, and calibrate lighting, water, and nutrient delivery for optimal production. These complementary technologies also permit the capture of data streams for which AI (still at early stages of deployment) offers high potential for analysis of crop yields, plant health, and other variables.

The bundling of these technologies creates feedback loops that enhance the operational performance of VF companies. For example: IoT-enabled sensors generate real-time environmental data, which AI algorithms immediately process, which then triggers automatic adjustments of LED lighting to optimize yields. In this way, the interplay of advanced technologies confers a competitive advantage over those VF companies that have not achieved high levels of technology integration.

Limitations of the study

We note three limitations of the study. While diverse in geography and other parameters, the survey sample comprises only 9 firms–a constraint imposed by the small population of commercially active VF companies, but one that limits statistical generalizability. Our case study firms were selected from among willing interview participants, introducing potential self-selection bias toward companies confident in their operational and strategic positioning. Finally, the study captures technology adoption at a single point in time. But given the rapid pace of change (particularly in AI and sensing technologies), longitudinal research would better track adoption patterns.

Because the survey targeted commercially active firms, the sample is limited to survivors of the industry contraction. The technology adoption patterns of failed first-wave companies are observable only through secondary sources, introducing survivorship bias that future research with archival or administrative data could address.

Practical implications

The study's key finding challenges the assumption that greater VF technological intensity necessarily improves competitive advantage. In practice, firms that survived the first wave industry turbulence emphasized disciplined technology adoption and operational economics. VF managers should therefore resist pressures to over-invest in too many technology domains unless those technologies generate clear and near-term business value.

Future research

Our study points to three directions of future research on technology and vertical farming: AI usage, factor costs, and biotechnology innovations.

The bifurcated responses on artificial intelligence –with half of the respondents initiating adoption of AI and the other half not yet considering it– deserve greater attention. This result could reflect uncertainty about the business value of AI or the relative novelty of AI-embedded technologies. Through expanded sample sizes and company use cases, future research can track AI adoption in the vertical farming industry as costs decline and commercial viability improves.

The second direction of future research focuses on factor costs of vertical farming across countries. The VF companies investigated in this study are based in developed markets: e.g., Germany, Netherlands, Sweden, United Kingdom, United States. For those high-income countries, labor costs were a key factor driving investments in automation, robotics, and related technologies. Future studies should explore dynamics of technology adoption in emerging/developing economies where factor costs–especially labor costs–as well as business practices and competitive conditions differ.

The third direction focuses on a technology vector–biotechnology–that did not surface in our study. The high failure rate of VF companies illustrated a critical challenge facing the industry: how to compete in low-margin commodity food markets employing a business model built on complex technologies with heavy capital costs. For failed first-generation companies, the consumer price premium over conventionally farmed products trumped the theoretical advantages of VF. Future research should explore innovations in biotechnology, notably applications of seed technology that promise to expand the domain of foods cultivated in enclosed structures and facilitate company migration from commodity to value-added products.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

DB: Resources, Visualization, Formal analysis, Data curation, Validation, Methodology, Software, Investigation, Writing – original draft, Supervision, Funding acquisition, Conceptualization, Writing – review & editing, Project administration. EC: Resources, Formal analysis, Software, Writing – review & editing, Writing – original draft, Methodology, Data curation, Investigation, Visualization, Project administration, Conceptualization, Validation, Funding acquisition, Supervision. EM: Investigation, Formal analysis, Writing – original draft, Data curation. HW: Investigation, Formal analysis, Writing – original draft, Data curation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. During the preparation of this work, the authors used Perplexity (GPT-5.1-based assistant) and Claude (Anthropic) to assist in identifying relevant literature and in editing for language and readability. These tools were not used for study design, data collection, data analysis, or drawing conclusions. All AI-assisted suggestions were independently checked, revised, and validated by the authors, who take full responsibility for the accuracy and integrity of the content.

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