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What is Controlled Environment Agriculture?

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Introduction to Controlled Environment Agriculture

Controlled Environment Agriculture (CEA) is a rapidly evolving, multidisciplinary, technology-based approach to the production of agricultural products under targeted environmental conditions. While some definitions of CEA extend the scope beyond crop production to include aquaculture, insect farming, livestock production, and even lab-grown meat, we will focus on CEA through the lens of horticulture crop production. CEA involves the manipulation of microclimates in partially or fully enclosed spaces to meet the unique needs of different plant species across their growth cycles (Gupta, Santosh, & Debnath, 2020). This approach allows for precise control of key inputs such as water, nutrients, chemicals, energy, and labor (Baghalian, Hajirezaei, & Lawson, 2023), resulting in improved produce quality, including enhancements in size, color stability, stalk strength, and shelf life (Tirki, Deepika, & Netravati, n.d.). CEA facilities range in their spectrum of control over environmental parameters and can include high tunnels or hoop houses, greenhouses, and indoor vertical farms (Fig. 1). Crops produced in CEA are typically grown in soilless culture.

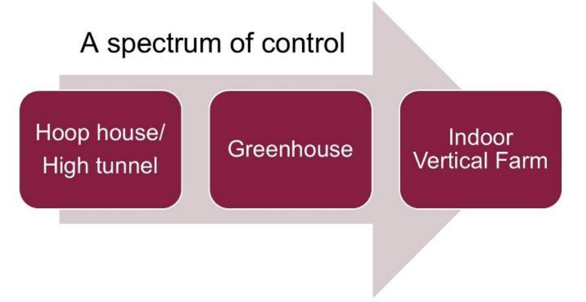

Figure 1. Spectrum of control over environmental parameters.

History of CEA

While CEA may seem like a modern innovation, its roots can be traced back centuries. The use of protected structures to enhance plant growth dates as far back as 14–37 CE in Rome, where early indoor agricultural techniques were used to cultivate *Cucumis* plants (Nemali, 2022). By the 1450s, Korea had developed heated floor structures to support citrus cultivation, and in the 17th and 18th centuries, France popularized orangeries, specialized greenhouses designed for citrus trees. The Wye House Orangery, built during this period, remains the oldest standing example in the United States. By the 19th century, Europe saw the rise of large glasshouse conservatories, expanding the role of controlled environments in plant cultivation (Nemali, 2022). The technological advancements of the 19th and 20th centuries further revolutionized CEA, with the introduction of supplemental lighting systems such as carbon-arc lamps, incandescent filament bulbs, high-pressure sodium (HPS) lamps, metal halide lamps, and eventually light-emitting diodes (LEDs) (Wheeler, 2008).

In Virginia, U.S., John Bartram documented greenhouse construction along the James River as early as 1739 (National Gallery of Art). By the 20th century, large-scale greenhouse operations became widespread, exemplified by the Doyle Florist Inc. / H.R. Schenkel Inc. Greenhouse Range in Lynchburg, VA (Fig. 2). From 1920 to 1990, these greenhouses were important producers in the VA cut flower industry. Lynchburg Grows purchased the greenhouse range in 2004 and now grows produce for local markets while also providing employment opportunities for individuals with disabilities (Indoor Ag-Con, 2024; Lynchburg Grows, n.d.).

Figure 2. Greenhouse photo from Doyle and Schenkel greenhouses (now Lynchburg Grows) in Lynchburg, Virginia. Photo Credit: Scott Lowman.

The term "Controlled Environment Agriculture" was introduced in the 1960s to describe horticultural techniques and technological innovations aimed at optimizing plant growth (Gomez et al., 2019; Hodges et al., 1968). Initially, early applications of CEA were largely concentrated in ornamental horticulture, particularly floriculture and bedding plant production, as well as transplants for container or field production. At the same time, edible crops continued to be cultivated primarily in open-field systems (Bethke & Lieth, 2016). However, with advancements in automation, climate control, and resource efficiency, CEA has expanded far beyond its original scope. Today, the industry continues to grow, incorporating a diverse range of crops and production methods.

CEA Structures and Soilless Culture

CEA encompasses a variety of production methods and systems, each with distinct characteristics. A **greenhouse** is a protective structure that regulates temperature, humidity, ventilation, and light, with the covering material being a key factor in performance. **Glass** provides excellent light transmission and durability but is costly and requires strong framing. **Double layers of air-inflated polyethylene film** are inexpensive and energy-efficient, though short-lived. **Fiberglass** offers good light diffusion but tends to yellow over time, while **polycarbonate** balances durability, insulation, and cost. **Acrylic** provides high clarity and longevity, but is more expensive. The choice of covering depends on climate, budget, and production goals (Gunter, 2022). In contrast, **high tunnels** or **hoop houses** are unheated, polyethylene greenhouse film or plastic-covered structures that offer some level of climate protection but lack the extensive environmental controls found in greenhouses.

Vertical farms, also known as plant factories or indoor farms, are agricultural systems in which crops are grown in stacked layers, often in highly controlled indoor environments. It is important to distinguish between **vertical farming**, which refers to the practice of growing crops in vertically stacked systems, and a **vertical farm**, which is a facility where this method is implemented.

In most cases, crops in CEA are produced in soilless culture, which refers to various methods of growing crops without soil. This includes container production - growing crops in containers filled with soilless substrates or media (e.g., peat or bark mixes). It also includes hydroponic production where nutrients are delivered through water to the plants, where the plants may or may not be supported by inert media (e.g., rockwool, oasis, clay pebbles). Widely used growing media or substrates used in hydroponics include perlite, coconut coir, rockwool, expanded clay pellets, and foam, each varying in water retention, drainage, cost, and availability, which influences irrigation frequency and root development (Cabrera Garcia et al., 2024).

Hydroponic Production Systems in CEA

Hydroponic production systems are commonly used in CEA to grow edible crops while conserving water, nutrients, and space (Table 1). These systems provide precise control over nutritional inputs, allowing for year-round cultivation and increased resource efficiency. Depending on the operation, systems can be purchased pre-made from suppliers, assembled through do-it-yourself (DIY) methods, or custom-built to match the specific CEA structure and crop requirements (Fig. 3). To learn more about hydroponic production, refer to the Hydroponic Production of Edible Crops VCE factsheet and video series (https://www.pubs.ext.vt.edu/content/pubs_ext_vt_edu/en/SPES/spes-466/spes-466.html).

Table 1. Description of common hydroponic production systems.

System Type	System Description
Nutrient Film Technique (NFT):	Thin nutrient film flows through sloped channels, supplying roots with nutrients and oxygen; highly efficient for leafy greens and herbs.
Deep Water Culture (DWC):	Roots suspended in nutrient-rich, oxygenated solution; air stones maintain oxygen for robust growth.
Ebb and Flow (Flood and Drain):	Root zone periodically flooded and drained to provide hydration and aeration; suited for larger or flowering crops.
Drip System (Bato or Duch bucket or strawberry trough):	Nutrient solution dripped to the plant base for precise hydration; commonly used for tomatoes, peppers, strawberries, and cucumbers (Fig. 4).
Wicking System:	Passive system where a wick draws nutrients from a reservoir; simple, low-maintenance, ideal for small-scale setups.
Aeroponics:	Roots suspended in air and misted with nutrient solution; maximizes oxygen exposure and nutrient uptake, requires precise control.

In addition to these hydroponic systems, **aquaponics** represents a related form of soilless agriculture that integrates hydroponic plant production with aquaculture. In this symbiotic environment, fish or crustacean waste is broken down by beneficial bacteria into plant-available nutrients, while the plants in turn help purify the water for aquatic life (Rakocy et al., 2006). Many of the hydroponic systems listed above—such as NFT, DWC, and drip systems—can also be adapted for aquaponic production, offering an ecologically sustainable model that maximizes resource use efficiency and diversifies production beyond crops to include fish or crustaceans.

What are we controlling in CEA?

Optimizing environmental conditions is fundamental to maximizing crop productivity, nutritional quality, and plant health in CEA (Dsouza et al., 2023). CEA allows growers to control environmental conditions and implement protective measures that maximize yields while minimizing stress from temperature extremes, drought, pests, and diseases. The extent of control varies between CEA production facilities due to structure and system types and design, and automation level. For example, for temperature control, a high tunnel may raise the plastic on the sides to increase airflow, while a greenhouse uses methods including vents, shade cover, exhaust fans, and a cooling pad, and an indoor vertical farm may use a building's Heating, Ventilation, and Air Conditioning (HVAC) system.

Figure 3. Active greenhouse with LED lights, fans, and cooling pads.

CEA production facilities can utilize sophisticated technologies to achieve precise controls. Internet of Things (IoT) sensors, automated control systems, simulation models, and advanced structural designs provide real-time monitoring and automated adjustments to environmental variables (Martinez, 2024). LEDs, for instance, offer energy-efficient, spectrum-customizable lighting that enhances photosynthesis while reducing operational costs. Likewise, controlled humidity supports continuous growth, vibrant flower coloration, and extended post-harvest life. It is regulated using ventilation systems, humidifiers, and dehumidifiers to balance moisture from transpiration and floor evaporation (Slathia et al., 2018).

Key environmental factors that can be controlled in CEA include:

- **Light:** Optimized in spectrum, intensity, distribution, and photoperiod to enhance plant growth, morphology, and quality (Baghalian et al., 2023).
- **Temperature:** Precisely controlled to optimize plant physiological processes, prevent stress-induced damage, and support consistent growth and quality, with particular attention to maintaining conditions that reduce disease susceptibility and enhance post-harvest longevity (Darras, 2020).
- **Irrigation:** Applied through various methods, selected based on crop requirements and the specific protected cultivation structure (Slathia et al., 2018).
- **Humidity and Airflow:** Properly managed humidity and airflow are essential for maintaining healthy plant growth. They ensure effective transpiration and nutrient movement, create uniform growing conditions, and promote photosynthesis, while also reducing the risk of disease associated with excess moisture (Cabrera Garcia, Milhollin, & Ernst, 2024; Hort Americas, 2021).
- **Fertilizers:** Carefully managed to provide all essential nutrients in appropriate concentrations, ensuring optimal plant growth, nutrient uptake, and development. Proper fertilization maximizes nutrient availability while minimizing the risk of deficiencies, toxicities, or nutrient imbalances (Cabrera Garcia, Milhollin, & Ernst, 2024).
- **Growing media or substrate:** Media can enhance irrigation efficiency, promote consistent nutrient delivery, and improve overall crop performance, making it a key factor in optimizing soilless cultivation systems (Cabrera Garcia, Milhollin, & Ernst, 2024).
- **CO_2:** Enriched to boost photosynthesis and biomass accumulation (Amarasinghe, Polwaththa, & Suratissa, 2025).
- **Insect and Disease Management:** Management strategies often include preventative measures, sanitation, biological control, and limited, strategic chemical applications.

Crops Found in CEA

CEA enables the cultivation of a wide range of plants, which can be categorized into food, medicinal, and ornamental crops.

Food Crops:

For food crops in the U.S., CEA production is led by tomatoes at 59%, followed by fresh herbs (12%), cucumbers (7%), lettuce (6%), peppers (3%), strawberries (1%), and other crops (12%) (Dohlman et al., 2024). Culinary herbs such as basil, cilantro, dill, parsley, and mint, along with leafy greens like spinach, kale, arugula, and specialty lettuces, are widely cultivated in controlled environments. Among these, leafy greens and microgreens are especially profitable due to their rapid growth cycles and premium local pricing (Martinez, 2024). Large-scale operations have also shown consistent success with strawberries, herbs, tomatoes, and specialty lettuces, underscoring CEA's ability to reliably produce perishable, high-value crops (McGowan et al., 2024).

Figure 4. Strawberries grown in Dutch or Bato bucket hydroponic systems

Beyond staple vegetables, CEA has expanded into high-value specialty crops. In Italy, a container farm produced 2 kg of saffron pistils in 70.4 m² over nine cycles per year, matching the yield of 1,000 m² of field production, while meeting first-category quality standards (Greatit, 2023). In Israel, Vanilla Vida achieved the world's first large-scale greenhouse harvest of *Vanilla planifolia*, cutting time to bloom in half and boosting vanillin yields to meet global demand (Watson, 2025). Similarly, Planted Detroit has demonstrated the potential of edible flowers as a CEA crop, using vertical farming and hydroponics to ensure uniform growth, multiple harvests per year, and reduced water use, while minimizing pesticide reliance (Planted Detroit, 2025) (Fig. 5). These cases highlight how CEA enables stable, sustainable, and profitable production of both staple and specialty crops.


Figure 5. Edible flowers in the Controlled Environment Agriculture Innovation Center vertical farm

Mushrooms provide another compelling example. As the highest-value food crop grown under protection in the U.S., they account for 57% of sales while occupying just 19% of production area and 7% of operations (Resource Innovation Institute, 2024). Mushrooms such as Oyster (*Pleurotus ostreatus*), Shiitake (*Lentinula edodes*), Lion's Mane (*Hericium spp.*), Chestnut (*Pholiota adiposa*), King Trumpet (*Pleurotus eryngii*), and Maitake (*Grifola frondosa*) thrive in carefully managed humidity and temperature conditions ideally suited for indoor systems (Cornell Small Farms Program, n.d.). By fine-tuning temperature, humidity, light, and CO_2 levels, CEA supports year-round mushroom cultivation with multiple harvests per cycle, often outpacing traditional outdoor production in efficiency. Notably, mushrooms also bridge the food and medicinal sectors. Their rapid market growth is fueled not only by food demand but also by rising applications in cosmetics, natural health products, and medicinal supplements. This dual role makes them an ideal transition into the broader category of medicinal crops.

Medicinal Crops:

As technology and innovation advance, CEA is increasingly being explored for the cultivation of pharmaceuticals, botanical drugs, dietary supplements, and recombinant products (Dsouza, Dixon, Shukla, & Graham, 2025). *Cannabis* production has become a leading example of CEA adoption, as growers leverage tightly controlled environments to improve yield consistency and cannabinoid profiles (Magagnini et al., 2018). This success highlights the broader potential of CEA for medicinal crops.

Controlled environments allow for precise management of plant growth factors, which are especially valuable for producing consistent concentrations of bioactive compounds. For instance, *Artemisia annua* (sweet wormwood), used to produce the antimalarial compound artemisinin, has been successfully grown indoors under LED lighting, leading to more reliable and higher yields. (Carlessi et al., *2022*). Likewise, *Catharanthus roseus* (Madagascar periwinkle), a source of cancer-fighting compounds such as vinblastine, has shown improved production when cultivated under controlled indoor lighting and nutrient conditions (Quadri et al., *2025*). These examples show how CEA can help growers produce consistent, high-quality medicinal plants while minimizing risks from unpredictable weather and pest pressures (Dsouza et al., 2025).

Ornamental Crops:

Ornamental crops have long been a cornerstone of CEA, particularly within greenhouse production systems. Greenhouses provide the precise environmental control necessary to maintain the uniformity, color vibrancy, and structural quality that ornamentals demand, ensuring strong market value. Commonly cultivated examples include bedding plants such as petunias and pansies, tropical and indoor species like orchids and bromeliads, and cut flowers such as zinnias, roses, and carnations (Tirki et al., n.d.). Beyond meeting consumer demand for year-round availability, protected cultivation allows producers to synchronize flowering times, extend market seasons, and reduce the risk of weather-related losses. In addition, the ornamental sector often serves as an innovation driver in CEA, with advances in lighting, climate regulation, and nutrient delivery frequently tested in flower and foliage production before being applied to food crops (Darras, 2020). This makes ornamentals not only a historic but also a strategically important crop category within the broader development of controlled environment systems.

Controlled Environment Agriculture Industry

The CEA edible crop industry production has experienced rapid growth in recent years, driven by technological advancements, increased private investment, and a surge in consumer demand for sustainable, locally produced food. According to the USDA's 2024 Economic Information Bulletin titled *Trends, Insights, and Future Prospects for Production in Controlled Environment Agriculture and Agrivoltaics Systems*, the number of CEA operations doubled between 2009 and 2019, reaching 2,994, with production increasing by 56% to 786 million pounds. This growth underscores the sector's expanding role in food production (Dohlman et al., 2024).

CEA's versatility allows it to be implemented in various forms, from standalone businesses to integrated systems within larger, field-based farms. Standalone CEA operations, such as vertical farms and hydroponic greenhouses, are designed to operate independently, often in urban settings, and to provide fresh produce close to consumers. These systems are particularly advantageous in areas with limited arable land or challenging climates. Conversely, CEA can also be integrated into traditional field-based farms, enhancing productivity and sustainability. For instance, high tunnels and greenhouse systems can be used for plant propagation, extend growing seasons, and improve yield consistency. In contrast, aquaponics systems can utilize fish waste to fertilize crops, creating a symbiotic relationship between plant and animal production.

The CEA industry is multifaceted, encompassing not only growers but also a vast network of suppliers and service providers. Key contributors include plant material suppliers, system manufacturers, lighting and climate control technology developers, automation and software companies, and fertilizer companies. This interconnected ecosystem supports the industry's growth by facilitating innovation, improving efficiency, and reducing operational costs.

Economically, the CEA industry presents both opportunities and challenges. While it offers the potential for high-value crop production and year-round harvests, it also involves significant capital investment and operational costs. The USDA report (Dohlman et al., 2024) highlights that while CEA can be profitable, especially for high-value crops, economic feasibility varies based on factors such as scale, location, and energy costs. For small-scale or early-stage ventures, managing these expenses is crucial for achieving profitability.

In summary, the CEA industry is a dynamic and evolving sector that offers diverse opportunities for growers, investors, and communities. Its adaptability to different scales and integration models, coupled with ongoing technological advancements, positions CEA as a key component in the future of sustainable agriculture.

Advantages of Controlled Environment Agriculture

The number of farms that are using controlled environments to produce edible and medicinal crops is growing (Dohlman et al., 2024; Stallknecht & South, 2025). CEA offers a multitude of benefits across social, environmental, and economic dimensions. As the sector continues to evolve, it presents practical solutions to agricultural challenges while opening new opportunities for innovation, sustainability, and food security.

Climate Resilience and Environmental Sustainability

CEA serves as a critical tool in mitigating the impact of extreme weather events such as droughts, floods, and heatwaves, which threaten field production systems. By cultivating crops in controlled environments, CEA minimizes reliance on external climate conditions and enables year-round production. CEA systems also provide more opportunities for exclusion prevention methods in integrated pest management programs to reduce the use of synthetic pesticides. These features contribute to environmentally sustainable practices and position CEA operations to take advantage of green investment incentives such as programs or funding opportunities that encourage environmentally responsible agriculture (McGowan et al., 2024). Incentives such as grants, low-interest loans, or tax credits for resource-efficient practices help CEA to support broader goals of environmental stewardship and economic resilience.

Energy and Resource Efficiency

CEA systems can improve environmental sustainability by integrating renewable energy sources such as solar, geothermal, wind, and biomass, which can significantly reduce operational costs and greenhouse gas emissions. Solar photovoltaic panels, ground-source heat pumps, and biomass boilers can supply a large share of heating, cooling, and electricity needs, while hybrid systems can meet energy demands entirely.

While vertical farms significantly outperform field systems in yield per unit area and resource efficiency (e.g., using less water and minimizing nutrient losses), they remain energy-intensive due to their reliance on sole-source lighting and complete climate control. Even when powered entirely by renewable energy, vertical farming currently exhibits a higher carbon footprint per kilogram of lettuce compared to open-field production, though this gap may narrow as renewable integration, material innovations, and energy-efficient technologies advance (Vatistas et al., 2022). Locating vertical farms near consumers can further reduce transportation and refrigeration emissions, helping to offset part of their operational impact.

Urban Proximity and Reduced Food Miles

CEA operations can be located near urban centers, where over half of the global population resides (Food and Agriculture Organization of the United Nations, 2017). By bringing production closer to consumers, urban and localized farming practices provide year-round access to fresh crops, even in areas where space and climate limit traditional agriculture. This proximity reduces food miles, resulting in fresher produce with improved taste and nutritional value. Shorter transportation times help CEA-grown products retain more nutrients and natural flavors, meeting growing consumer demand for local, fresh, and sustainable food. The result is a more resilient and efficient food system capable of addressing urban food insecurity (Kalantari, Mohd Tahir, Mahmoudi Lahijani, & Kalantari, 2017).

Crop Diversification, Quality, and Market Expansion

CEA enables growers to expand beyond traditional crops and cultivate a diverse range of plants, including specialty crops and crops for pharmaceutical purposes. There is an opportunity with CEA to produce high-value crops for fresh and value-added markets as well as crops used for vaccines, dietary supplements, and cosmetic ingredients. CEA can enable the production of fresh produce that would not otherwise be available in a season or region, which can enhance dietary variety and strengthen food security, opening new revenue streams for producers (McGowan et al., 2024). Yields under controlled or protected cultivation are often four to five times greater than those of open-field agriculture for high-value vegetable crops such as tomatoes, cucumbers, capsicum, and leafy greens. These systems allow growers to achieve significantly higher returns per unit of land while benefiting from extended harvest periods and year-round production (Kumar et al., 2007; Mayanglambam & Thakur, 2013).

Social Impact, Employment, and New Entrants

CEA presents a promising avenue for economic development, particularly in underutilized or barren lands. By establishing production facilities near urban and underserved areas, CEA enhances local food resiliency, reduces post-harvest losses, improves access to nutritious foods, and generates meaningful employment opportunities across communities (Boyd et al., 2025). Socially, CEA is attracting youth and tech-savvy entrepreneurs, including those with backgrounds in engineering, computer science, and sustainability, who might otherwise avoid farming (Slathia et al., 2018; McGowan et al., 2024). The integration of modern technology, predictable growing conditions, and climate-controlled work environments makes CEA an appealing long-term career path and encourages new entrants to explore small- to medium-scale farming ventures, modernizing the agricultural sector while driving economic and social growth.

Figure 6. A vertical hydroponic system is used to build interest in the classroom.

Challenges Facing Controlled Environment Agriculture

While CEA offers many advantages and opportunities to tackle challenges faced by agriculture, it also faces a broad set of technical, economic, environmental, and socio-cultural challenges. These hurdles must be addressed to ensure the scalability, environmental sustainability, and long-term viability of the industry.

Energy Demand

CEA is energy-intensive, requiring significant inputs for lighting, climate regulation, CO_2 enrichment, and automation systems. Energy demands are also amplified using advanced automation systems, such as hydroponic pumps, climate sensors, and robotic harvesting tools, which run continuously to maintain productivity. The reliance on non-renewable energy sources rather than renewable alternatives contributes to a larger carbon footprint in CEA compared to traditional field-based farming (Hallikainen, 2018; Kikuchi et al., 2018a; Wildeman, 2020).

High Start-Up and Operational Costs

The initial investment required for constructing and equipping CEA facilities (e.g., greenhouses, vertical farms, lighting systems, climate controls) is substantial. Ongoing operational costs, particularly electricity, maintenance, and skilled labor, significantly challenge profitability in small-scale or early-stage CEA ventures. Lighting alone can consume 65–85% of total energy, with HVAC and climate control adding substantially to the energy load (Arcasi, Mauro, Napoli, Tariello, & Vanoli, 2024). Maintaining optimal temperature and humidity, along with the energy required to pump water across multiple vertical layers, also contributes to high operational expenses (Lubna, Lewus, Shelford, & Both, 2022). This energy-intensive nature makes small CEA setups particularly vulnerable, as they often lack the scale and financial flexibility to offset such high recurring costs, reducing their paths to profitability.

Consumer Perception and Marketing Challenges

Despite technological sophistication, many consumers are skeptical of CEA-grown produce, perceiving it as less “natural” than field-grown alternatives. Terms like “controlled environment” can reinforce perceptions of artificiality. Limited public awareness, coupled with ambiguous or inconsistent regulations, further hinders trust and complicates marketing, especially in markets where consumers prioritize naturalness and transparency (Perambalam et al., 2021). Marketing claims like “organic,” “sustainable,” or “pesticide-free” may also face scrutiny if facilities rely on synthetic inputs or fossil fuels (McGowan et al., 2024). Bridging this perception gap will require transparent labeling, consumer education, and clearer definitions of production and environmental sustainability standards within CEA systems.

Inadequate Technical Knowledge and Skilled Labor Shortages

CEA requires a workforce proficient in plant science, engineering, data analytics, and automation. However, there is a persistent shortage of trained personnel to operate and maintain these complex systems (Tirki et al., n.d.). Even in regions where interest exists, inadequate technical training among growers hinders effective implementation (Tirki et al., n.d.). Expanding Extension services, training programs, and academic-industry partnerships is vital to building the talent pipeline necessary for sector growth.

Infrastructure, Post-Harvest, and Distribution Challenges

Insufficient post-harvest infrastructure, including storage, cold chains, and transport logistics, results in significant product loss and diminished market returns (Tirki et al., n.d.). CEA operations often function outside established agricultural systems, creating a separation that makes integration into broader food supply chains difficult. This disconnect limits economies of scale and prevents streamlined distribution, both of which are essential for long-term success (Burritt, Valle de Souza, & Peterson, 2025). In addition, packaging, branding, and consumer trust remain weak points for many CEA startups. Developing efficient cold-chain systems and forming retail partnerships are essential strategies to ensure quality maintenance and market penetration (McGowan et al., 2024).

Conclusions

The production of food and medicinal crops in CEA stands at a crossroads of promise and challenge. While the sector offers innovative solutions to global food security, climate resilience, and nutrition, it also faces barriers, including high energy demand, limited crop diversity, and ongoing operational costs that complicate scalability. Addressing these limitations will require coordinated progress in research, technology, policy, and investment.

The future of edible and medicinal crop production in CEA depends on innovation and the integration of traditional agriculture knowledge into CEA production practices and technologies. CEA systems can be adapted to any scale, community, and school garden, to small, medium, and large commercial operations, to operations that are solely focused on CEA or use CEA in addition to field crop production, with varying levels of automation and environmental control. Increasingly, small and medium-scale edible crop growers are finding success by targeting niche markets, demonstrating that CEA can be profitable and practical beyond large-scale facilities. Continued advances in technology, such as AI-driven climate control, renewable energy, and crop breeding, will further enhance efficiency and expand crop diversity. Collaboration among farmers, engineers, horticulturists, business leaders, and environmental scientists, supported by strong Extension programs, will ensure that new knowledge and technologies are developed, keeping the crop needs, profitability, and environmental sustainability in mind.

Another critical frontier is education and workforce development. Beyond training professionals in robotics, data science, energy efficiency, and crop optimization, CEA is increasingly entering the classroom (Fig. 6). Schools, universities, and community colleges are adopting vertical hydroponic systems and other controlled growing technologies as teaching tools to inspire students, build agricultural literacy, and prepare the next generation of growers and innovators. This integration of hands-on systems into learning environments broadens the reach of CEA, cultivating both a skilled workforce and a more informed public. It also provides exposure to agriculture to students who may not otherwise have the opportunity to learn about the agriculture industry.

Beyond productivity, CEA has a unique role in advancing health, equity, and community connection. By building production facilities near urban and underserved areas, CEA can expand access to fresh produce, reduce supply chain vulnerability, and build consumer trust through transparent farm-to-table systems. At the same time, opportunities in specialized and niche markets, such as pharmaceutical crops, organic produce, and sustainability-focused systems, open new economic pathways for both established companies and small to mid-sized growers, including marginalized communities.

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Additional Resources

Controlled Environment Agriculture Innovation Center website: https://ceaic.org/extension-education/additional-resources/

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