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# Controlled Environment Agriculture and Its Ability to Mitigate Food Insecurity

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## Abstract

The research objective of this review is to discuss the rationale that led to the development of Controlled Environment Agriculture (CEA) and investigate this agricultural approach as a potential solution to mitigate the increased pressures on food security. It describes the need for urban cultivation systems using controlled environments and how they can be harnessed to address pressures facing food security. The factors that have contributed to the growth of CEAs, education, environmental justice, and the advantages and disadvantages of growing crops in CEAs in urban areas will be discussed. The article reviews global urban cultivation systems using controlled environments, by identifying the technologies needed to establish them. The practice of CEA is being increasingly adopted worldwide and we describe urban agriculture and compare it with traditional growing systems. Indoor farming systems that integrate into existing urban infrastructure such as vertical farming and plant factories using CEAs are discussed. Indoor farming gives urban areas enhanced access to food sources, but the cost is high, however decreasing due to recent technological advances. The current review extends the literature by incorporating recent research on the topic of agriculture in urban areas and food security. This review seeks to provide additional information regarding the viability of CEA in urban areas.

## Keywords

Controlled Environment Agriculture, Environmental Education, Environmental Justice, Food Deserts, Urban Agriculture

## 1. Introduction

Humans need diets that include nutritious foods, such as fruits, vegetables, nuts, and fish to lower their risk of health issues, such as cardiovascular disease [1]. However, feeding the world a nutrient-rich diet presents challenges for several reasons, such as a growing population, a reduction in arable land, and an escalation in weather extremes from climate change [2]. Béné *et al.* [3] studied the associations between food system drivers, such as population growth, wealth, urbanization, and diet, and sustainability factors that reduce food insecurity through socio-economic and environmental aspects. The researchers found that the significant drivers were negatively correlated to sustainability, except for one economic aspect involving merchandise and service trade flows [3]. García-Oliveira, Fraga-Corral, Pereira, Prieto, and Simal-Gandara [4] further point out that the food system will not be able to sustain population growth without modifications, such as diet and innovative agricultural techniques. Instead of moving closer to meeting the United Nation's Sustainability Development Goals (SDGs) for ending world hunger, an estimated 828 million people did not have enough to eat in 2021, which is an increase of 46 million individuals from prior years [5]. The high concentration of people that reside in cities makes the issue of food access and sustainability especially important within urbanized areas [6].

Since traditional soil-based agriculture is resource-intensive according to Ragaveena, Shirly Edward, and Surendran [7] and Benke and Tomkins [8] indicate that arable land is a diminishing resource, we discuss another avenue of growing crops as a potential solution to mitigate food insecurity. Five innovative agricultural production methods were studied by Glaros *et al.* [9] as potentially sustainable alternatives to soil-based agriculture. The researchers concluded that Controlled Environment Agriculture (CEA) was more feasible than the other four methods of cellular agriculture, northern agricultural expansion, insects as a food source or entomophagy, and seaweed aquaculture [9]. Controlled environment agriculture is a closed-system novel farming method that uses a small footprint to grow crops [10]. Crops may be grown vertically in warehouses, buildings, shipping containers, or specially designed structures that allow the temperature and humidity to be regulated [11]. The novel GREENBOX technology developed by the Yang Laboratory at the University of Connecticut is an example of a structure where fresh crops may be grown in a technically and financially feasible way, especially useful when space is limited [12] [13]. CEA setups involve an outer structure, which houses tiered platforms that hold crops while allowing for optimal nutrient delivery within a controlled setting [14]. Plant growth is enabled through lighting and other devices, such as dehumidifiers and fans [14]. CEAs, such as plant factories, use fewer natural resources, such as water and carbon dioxide, and are more efficient than greenhouses [13] [15]. CEAs offer many advantages for agriculture in urban areas by placing crop production near the consumer, which shortens the distance it travels and saves energy [8] [11] [16] [17]. CEAs not only save trans-

portation costs when compared with traditional farming and thereby reduce energy usage, but they also permit year-round production, which is limited by seasons in conventional methods [8]. The aim of this paper by the APS Laboratory for Sustainable Food at Florida Gulf Coast University is to discuss the motivations that led to the development of CEAs and investigate this agricultural method as a potential solution to the increasing pressures on food security. The factors that have contributed to the growth of CEAs, education, environmental justice, and the advantages and disadvantages of growing crops using CEAs in urban areas will be discussed.

## 2. Controlled Environment Agriculture

The term, controlled environment agriculture, has been around since the 1960s [18] [19]. Despommier [20] initially envisioned the benefits of using CEAs and vertical plant factories, which featured a closed system to relieve the problems of traditional agriculture in urban areas (*i.e.* pests, pollution, waste, etc.). Benke and Tomkins [8] suggest that new ideas should be considered for CEAs, such as re-purposing abandoned buildings or placing them underground.

CEAs use artificial lighting for plant photosynthesis [21]. Hashimoto [22] explained that CEA setups use cultivation elements, just like a manufacturer operates an assembly line during production. Six main elements are needed for CEA setups: 1) a structure that is thermally insulated with non-transparent walls; 2) a multi-tiered system that accommodates crops and lighting; 3) pumps to remove heat generated by lights and dehumidify the unit; 4) carbon dioxide delivery unit to enhance photosynthesis; 5) nutrient delivery system; and 6) environmental control units for electric and pH regulation to support nutrient flows [14]. **Figure 1** presents an illustration of the main components of a CEA setup.

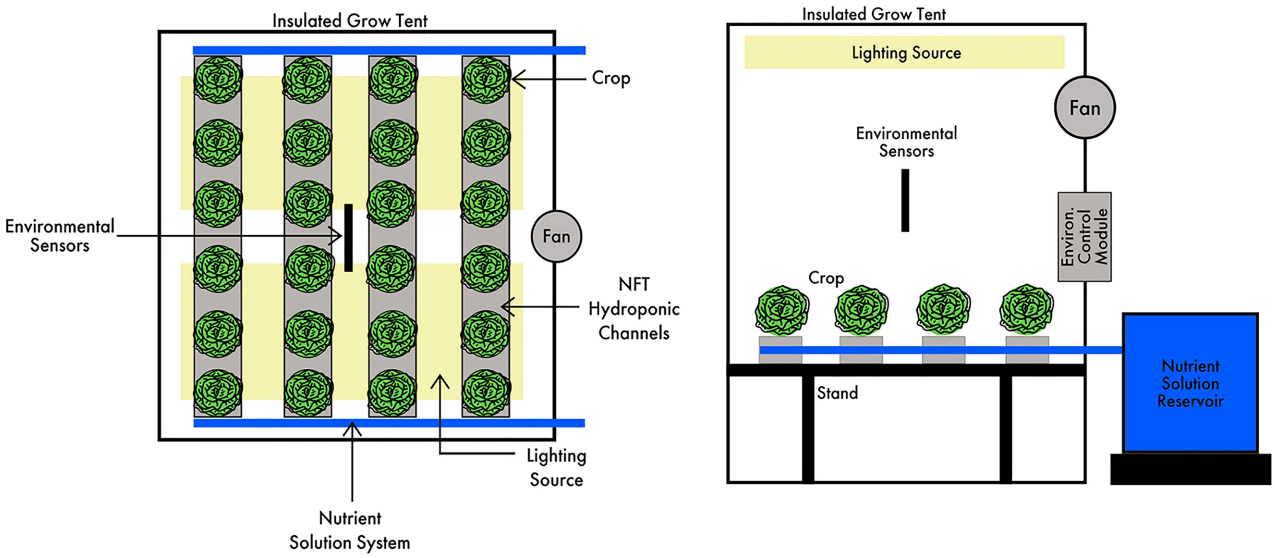


**Figure 1.** An illustration of the main components of a Controlled Environment Agriculture (CEA) setup which include thermally insulated walls, a soilless cultivation system, and environmental controls and sensors, top view (left), and front view (right).

## 3. Factors That Have Contributed to the Emergence of CEA

### 3.1. Food Consumption Driven by Rising Populations

Population growth has increased the rate of food consumption. The global population has tripled since 1950 [23] and is expected to continue growing [24]. The world's population is estimated to be 8 billion in 2022 and it is expected to increase to 10.4 billion by 2100 [23]. This increased growth pressures the food system as the increase in population creates more demand.

### 3.2. Increase in Wealth

Increases in wealth give people more money to spend on food. By 2030, the middle class is expected to grow by 3 billion people and this increase in wealth is expected to change dietary consumption [25]. Baldos and Hertel [26] studied the effect of income growth from 2006 through 2050 and found that this increase generated a twenty-four percent increase in calorie consumption. Wealthier individuals tend to eat more nutritious and healthy diets [27]. Purchasing power increases as incomes rise, which places additional pressure on the food production system, all while natural resources such as land and water face stiff competition [28].

### 3.3. Urbanization

The population is denser in cities, which means that food consumption is higher than in rural areas. A little more than half or 55 percent of the world's population in 2018 lived in urban areas [29]. In 1950, only 751 million people were in urban regions worldwide, and this number grew to 4.2 billion in 2018 [29]. This urban concentration is predicted to grow to 68 percent by 2050 as the trend towards urbanization in countries such as India, China, and Nigeria increase by 35 percent. As of 2018, only 3.4 billion people live in rural areas across the globe [29]. The rural population is expected to peak and then fall to 3.1 billion by 2050 [29].

Lim and Kashnani [30] refer to the cultivation of crops within city boundaries as urban agriculture. Cities cover between 300 to 700 thousand $km^2$ of land on Earth [31]; whereas agricultural land encompasses 48 million $km^2$ [32] [33]. Prior to the 1950s, agricultural produce was trucked in from farms located at the cities' edges or city residents maintained small gardens [34]. After the war, spurred by the economic boom, technological advances improved industry, agriculture, and technology, displacing suburban farms with commercial infrastructure [34]. Farms moved to rural areas where the land was cheaper. The land occupied by urban gardens became more expensive and was sold for commercial use [34]. Food is produced on land the size of South America to feed the worldwide population, and an additional area the size of Brazil (*i.e.* another 2.1 billion acres) will be needed to supply the increasing population [35] [36].

CEA in urban areas reduces food miles by shortening the distance food travels

from production to the consumer. Specht *et al.* [16] illuminated the problem of energy expended to bring food to the consumer (*i.e.* food miles). Weber and Matthews [37] calculated that the average food miles in the United States is 1020, and the entire supply chain is 4200 miles long. Coley, Howard, and Winter [38] expanded upon the idea of food miles by concluding that, based on the number of food miles, consumers may choose to eat locally produced food.

Some of the attractive qualities of agriculture in urban locations, such as increased food nutrition and higher crop yields, have stimulated global interest [39]. Agriculture in urban areas makes food more available, and accessible to urban residents, which reduces food instability, and promotes a sustainable food program [40]. Global economies of all types are finding applications and increasing their use of agriculture in urbanized locations [41]. One of the non-food activities that urbanized agriculture cultivates is new job opportunities [42].

By the year 2030, over sixty percent of the global population will live in cities [43]. Urbanization is changing land use, which has socioeconomic and biophysical implications [42]. When looking at a macro-level, land-use alterations from land clearing influence the level of precipitation throughout the ecological system, having a cascading effect on global diversity from these anthropogenic impacts [44]. Plant factories improve environmental sustainability by reducing the amount of irrigation, use of land for crop production, and application of pesticides; furthering societal goals by increasing employment opportunities; and increasing economic sustainability by producing crops with higher yields and quality that are grown near consumers [14]. The use of CEAs in urban areas has the advantages of being connected with its' socioeconomic and ecological aspects, as well as the physical piece of urban food production [45]. Agriculture in urban areas performs the function of providing sustenance from fresh produce with better nutrients, economic growth through additional job opportunities and cost savings, environmental quality through more diversity, and managing ecosystem services, such as waste [46]. Diehl *et al.* [47] identified that the use of agriculture in urban areas by city planners can help alleviate metropolitan challenges. Bohn and Viljoen's [48] "edible city" is made possible through a continuous productive urban landscape or bringing prolific landscapes into the planning process, which is an essential part of making cities sustainable.

### 3.4. Nutrition and Health-Related Issues

Plants have therapeutic properties which reduce stress and anxiety levels in patients [49]. Relaxation, along with food nutrition and quality, and physical associations with nature, are some of the main benefits of agriculture in developed urban areas [45]. Gundersen and Ziliak [50] reviewed the literature on relationships between food insecurity and health in the United States and Canada and found a negative association, which was intensified for children and the elderly. The authors identified that food insecurity may affect people's physical, emotional,

and cognitive health [50].

## 4. Food Supply and Production Factors

### 4.1. Agriculture Is Resource-Intensive

Agriculture and the processes that bring products to consumers are energy-consuming and require extensive use of resources, an estimated 30 percent of global energy to meet their demand [51]. It is important to study the impact that agriculture has worldwide because agriculture accounts for most of the water, 72% that is consumed globally [52]. Energy is consumed in the agricultural processes in five ways: 1) farm storage; 2) transportation from farm to sales location; 3) warehouse storage; 4) employee sales travel; and 5) sales to the end user [53]. Ragaveena, Shirly Edward, and Surendran [7] suggest that agricultural processes need to reduce the use of natural resources while increasing crop yield per acre for food production to become sustainable.

### 4.2. Soil Quality Degradation

The surge in population and increase in food consumption has impacted soil quality. Degradation in the soil is important because soils help control flooding, regulate carbon, and prevent carbon dioxide from being released into the atmosphere as a greenhouse gas, in addition to acting as a base material for farming crops [54]. Humans impact soil through the over-application of fertilizers, erosion when leaving the ground bare in between plantings, storing waste, and increased acidification from poor irrigation techniques that affect soil pH [54]. Future food production is at risk from soil degradation [54].

### 4.3. Severe Weather Events

Greenhouse gas emissions have influenced the Earth's climate by triggering a 1.5˚C predicted increase in temperature over the next twenty years [55]. This increase in temperature will affect the weather by making the sea levels rise from melting glaciers [55]. Food systems need to be more energy efficient, while also taking the environment and climate into consideration when supplying urban areas [56] [57]. Food systems contribute to severe weather events through the release of greenhouse gas emissions and have vulnerabilities to climate change [58]. Increases in temperature from climate change affect crop harvests and livestock production through droughts and other severe weather [58].

### 4.4. Pandemic Impact on Food Supply Chain

Food production systems have become separated from consumers by distance attributed to increased globalization [56]. Hailu [59] states that the food system was stressed by the impacts of border closures, shortages in the labor supply, and decreased trade due to the COVID-19 pandemic. The food supply chain challenges from the pandemic have encouraged the idea that the food supply chain

of the future will have less of a global emphasis and become more localized [60].

### 4.5. Technological Innovation

Agriculture is benefitting from technological innovations like smart farming, which uses big data analytics, and machine learning to optimize nutrient delivery for optimal plant growth [7]. The initial costs are expected to decrease over the years as plant factories become more efficient [14]. One way that production costs will become lower is by increased control of the root growth while not limiting the plant's growth [14]. Heat recovery system advances will increase the efficiency of plant factories [10]. The availability of improved ion sensors that have a longer lifespan for nutrient detection will lower costs [14]. Improvements in the various CEA components and improved production processes will reduce CEA costs through advancements in technology.

## 5. Food Insecurity

Food insecurity occurs when people do not have sufficient access to food that is nutrient-rich enough to meet daily requisites for a healthy life [61] [62] [63]. Across the globe in 2017, one in every four people experienced food insecurity [64] [65]. The lack of self-reliant food systems was especially visible during the COVID-19 pandemic [46]. The projected number of food-insecure people doubled from 135 million to 265 million in 2020 from the COVID-19 pandemic [46].

### Food Deserts

Food deserts are populated areas with reduced availability and retail access [66] to fresh nutritious foods. They are spaces that are missing affordable, nutritious, and fresh foods that constitute a healthy diet [67]. Food deserts develop when major chain supermarkets are unwilling to locate their stores in the inner city or low-income neighborhoods, usually moving outwards to the suburbs [63] [68]. The lack of profitability and higher overhead costs make large grocery stores reluctant to place stores in food deserts and low-income areas that have higher crime rates [68] [69]. Insurance rates are higher in low-income areas and grocery stores struggle to get building loans [63].

Vulnerable populations that are more likely to reside in food deserts are impoverished, ethnic minorities, older individuals, or those who are in poor health [70] [71]. Food retailers tend to provide fewer services to African Americans, Latinos, and other socioeconomically disadvantaged individuals in industrialized countries [72]. Low-income families eat less healthy diets as they lack access to purchase fresh foods [70] [27]. The deficiency of nutritious food has been associated with an increased risk of obesity, cardiovascular diseases, and depression [50] [73]. Families with children that are challenged socioeconomically tend to develop obesity and diabetes [74], which incur $327 billion annually in medical expenses and indirect costs such as absenteeism [75]. Thomaier *et al.* [76] sug-

gest that the food supply of cities can be improved by plant factories that use zero land for crop production.

## 6. Education

With the increase in urbanization, younger populations have not developed a connection to plants, nature, and the environment [77]. Lineberger and Zajicek [78] found that the best time to teach people about the nutritious aspects of fruits and vegetables is in their youth. Educational programs at schools, such as school lunches, may influence the kids' dietary patterns to promote a healthy diet [4]. Student involvement in gardening increases their willingness to try fruits and vegetables, with a resulting preference for them in some cases [79]. School gardens interest educators because it gives opportunities to expand the curriculum and the students develop positive attitudes towards sciences like biology and chemistry [77] [80] [81]. A group of participating schools that had students and teachers farm indoors using shipping containers found the experience satisfying [81]. Education about agriculture in urban areas is important because a person's knowledge subjectively influences their attitudes about usefulness and sustainability [39]. Agriculture in urban areas will often involve volunteers to operate private farms [76]. The volunteers could be nearby residents who assist with educational and social programs, which enhance their knowledge about the food production system [76].

## 7. Environmental Justice

Agriculture in urban areas may help cities reach their food security goals by increasing the availability and access to nutritious food for people of all economic levels [82]. Kaljonen *et al.* [83] suggest that food systems inequities need to be addressed in addition to more productive and efficient agricultural methods. Unevenly, distributed income, wealth, and power limit individuals' access to nutritious foods [83]. While agriculture in urban areas could supply low-income households with fresh food, it is not necessarily serving the community in which it is produced due to cost [84]. Social inequities that factor in fresh food purchases by low-income households would benefit from the education that builds trust in food systems that produce fresh foods, along with improved infrastructure at corner markets in food-insecure neighborhoods [84]. Policies are needed to incentivize adding agriculture in urban areas that would provide for improved access to fresh produce and build economic equality [84]. Clark and Miles [85] suggest that the stakeholders in the community need to be empowered to make sustainable decisions to promote more just outcomes.

## 8. Advantages of Growing Crops in a Controlled Environment in Urban Areas

CEAs offer many advantages for urbanized food systems. CEAs can increase plant

production by environmentally controlling conditions regardless of the season [86]. One of the opportunities that indoor farming offers is optimal environmental settings by eliminating exposure to extremes in temperature, wind, and water, which can positively influence plant growth [87]. There are variations in environmental conditions over different seasons. Stable vegetable crops need to grow in controlled environment settings for continuous production [8] [20]. Since plant factories are closed systems that do not interact with the outdoor environment, they can produce crops regardless of changes in the outside weather [41]. Crop production using traditional farming is limited by seasons and severe weather events [8]. Traditional farming also subjects crops to pathogens and pests found outside of a controlled environment [87].

CEAs take less space than other plant production methods, which is an advantage in urban areas [10]. Son *et al.* [88] found that CEAs, also known as plant factories, can convert the carbon dioxide generated in urban areas into oxygen, which helps humans breathe. NASA has analyzed food production in space and determined that just 20 - 25 $m^2$ of crops provide enough oxygen for an individual to thrive [89].

In general, agriculture in urban areas supports building communities by promoting a sense of support, which reduces residents' isolation and sense of loneliness [90]. Placing agriculture in urban areas enhances social interaction as individuals work together to produce crops [17]. Urbanized agricultural projects can be incorporated into facilities such as nursing homes, prisons, and hospitals, which provide additional social benefits for urban areas [19].

## 9. Challenges of Growing Crops in a Controlled Environment in Urban Areas

While plant factories are closed systems that in some ways shield the plants from outside pests, the close placement of the plants and humidity have the potential to breed pathogens if not carefully controlled [87]. Another challenge of CEAs, or plant factories, is that food production is limited to mostly green leafy vegetables, such as lettuces, microgreens, tomatoes, and berries [8].

CEAs are costly to establish as the preliminary costs are high for several reasons. The high startup and operating costs associated with CEAs from building the structure, lighting, cooling, humidification, and labor is restricting development, especially considering the limited supply of crops that can be produced [17]. Some areas that increase the cost of CEAs are electricity expenses, equipment depreciation, and labor costs [91]. Electrical costs can be reduced by using LED lights with a high electric to Photosynthetically Active Radiation energy conversion coefficient, instead of fluorescent lights [92]. Advancements and improved access to lighting such as LED lights used to grow plants and monitoring equipment such as pH and nutrient dosing mechanisms have made CEAs a more viable option for large-scale urban production [93]. However, not all CEAs are expensive investments. For example, the GREENBOX technology developed by

the Yang Laboratory at the University of Connecticut costs only $398 to assemble and $157 each year in operating expenditures [94].

## 10. Controlled Environment Agriculture as a Tool to Mitigate Increased Pressures on Food Security

The food supply needs to keep up with the demand and not burden the environment. One way to encourage sustainability and better manage the environment is through growing crops in urban areas [95]. Food systems that can enhance plant production through regulated nutrient delivery, reduction in pesticides, better water preservation, and reduced waste offer prospects of achieving the goal of sustaining the growing population [87]. Muñoz-Liesa *et al.* [96] advocate that urban sustainable development can be uniquely supported by using circular-resource systems. Food security may be achieved through smart design and using advanced materials for optimizing specific crop growth while focusing on reducing material costs and waste in urbanized farm systems [87].

Janick and Paris [97] estimate that 2480 CEAs will be in place by 2026. Engler and Krarti [98] estimated that CEAs were worth $26.8 billion dollars globally in 2018. CEAs are projected to grow 9.19 percent from 2020 to 2025 [99]. Seven commercial CEAs are operating in New York City, most of which have a nexus to low-income areas [100]. Legislation has been put in place to allow for the construction and redesign of buildings for sustainability that includes provisions for agriculture in urban areas to eliminate possible obstructions to food system production [100]. Due to the feature of water recycling, CEAs are expected to be popular in areas where there is a scarcity, such as the Middle East, and Africa, and densely populated countries like Israel and Japan [8]. Singapore is using A-shaped indoor plant factory towers that produce ten percent of the vegetables for the city-state [8]. CEAs and soil-less systems are accepted and recommended for use in Africa, India, Europe, Australia, South America, and the Middle East, in addition to China, Japan, and Korea [101].

## 11. Conclusion

In summary, many factors, such as a sharp population growth that is driving the need for sustainable food production systems that are less reliant on natural resources, have prompted an interest in controlled environment agriculture. CEAs are possible solutions for the food insecurities caused by food deserts in urbanized areas. CEAs allow for year-round crop production that uses very little space and recycles water, making them ideal for urban settings. As technological advances continue to make CEA components more affordable, the use and implementation of this type of food production system will become more accessible. Urban residents will profit from the education, jobs, social, and economic benefits from nearby CEAs, in addition to health benefits from the available supply of fresh foods that will add nutrients to their diets.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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