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Controlled-environment agriculture and the implications of growing food indoors

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CIVE3430
Term Project Report

Abstract

Controlled-environment agriculture (abbreviated as CEA) is a budding agricultural technique in which crops are grown in enclosed spaces with technologically imposed controls over environmental conditions. This may include artificial heating or LED fixtures to replace sunlight. It is growing in popularity in response to the extractive nature of open-field farming, and as a way to deliver food more sustainably and reliably to the increasingly urbanized global population. In practice, implementations of CEA range from large complexes of greenhouses in rural Spain to technologically intensive soilless farms in the heart of New York City. This paper sought to evaluate CEA from the perspective of its environmental implications, relevant economic factors, and potential social impacts. Ultimately, current research indicates that CEA varies in its efficiency at achieving sustainable food production and distribution across various forms and locations. Environmental factors that were considered include demand for energy, land, and water, as well as emissions and biogeochemical cycling. Generally, less technologically intensive greenhouses strike a balance between energy consumption and thermal controls, with solar energy often supplementing energy demand without emissions. Vertical farms and hydroponics can greatly increase yield and water efficiency at the cost of increased energy demand, but economically they both fail to offset high operation costs. CEA farms that implemented intensive climate control measures for year-round cultivation were deemed to consume energy excessively to the point of being unsustainable. Since many current detriments of CEA, such as its dependence on non-renewable energy, are universally lessening with time, it's possible that CEA could eventually see widespread adoption in urban environments. However, more research is needed on CEA's potential to create more equitable food distribution systems, community opportunities, or nutrition education; and whether it is worth pursuing CEA as opposed to traditional methods of urban agriculture such as rooftop farms or community gardens.

Introduction

Some 12,000 years ago, humans, previously a nomadic species, learned to methodically harness the cultivation of crops and livestock for food, a system called agriculture. The resulting period, known as the Neolithic Revolution, was a sweeping transition of human development from tribes of hunter-gatherers to permanent agrarian settlements. Between ancient farming civilizations, feudal systems in the Middle Ages, and current post-industrialized factory farms and grocery stores, agriculture has played a pivotal role not only in human interactions with the environment, but also in the structure of society.

While food distribution is stabler than ever with the more automated and resilient systems of today, there are a number of factors that still prove to be problematic in modern agriculture. Demand for food has continually increased as Earth's population grows, with a further projected increase of around two billion people by 2050 estimated to compound current food demand by 70-90%. Additionally, two-thirds of the population is expected to live in urban areas that aren't agriculturally self-sufficient by 2050 (de Fraiture et al, 2014). Despite being able to produce enough food for 10 billion people, societies are unable to effectively distribute and maintain food supplies, as seen by the approximately 800 million people worldwide who remain food insecure (McCarthy et al, 2018). Climate change has contributed significantly to agricultural challenges, with inhospitable growing conditions occurring more frequently due to flooding, rising sea levels, and harsh weather. Industrialized factory farms are responsible for land degradation, resulting in fears of climate change causing a feedback loop between increased deforestation and inhospitable weather conditions for agriculture. Despite supplies of freshwater dwindling worldwide, current agricultural systems (including animal agriculture) represent 70% of water use across all sectors globally, a number that is projected to rise over time (Barbosa et al, 2015).

Alternative methods of agriculture seek to offer the potential for more environmentally sustainable and less ecologically intrusive methods of farming. One response to these agricultural challenges has taken for in controlled-environment agriculture (abbreviated as CEA). Broadly, CEA is the practice of growing crops in an artificial indoor setting. By building a bespoke facility in which crops are cultivated, growers can exact precise control over the environment in which crops are grown. This can be utilized to improve crop yield by improving land use efficiency, as well as reducing strain on municipal water supplies by optimizing and recycling water use (Graber et al, 2009). CEA also supposedly allows crops with particular conditions for growth to be grown in environments that normally wouldn't suit those conditions, which allows crops to be grown out-of-season. This paper aims to examine the multifaceted socioeconomic and environmental implications of the adoption of various types of controlled-environment agriculture as alternatives to traditional field-farming.

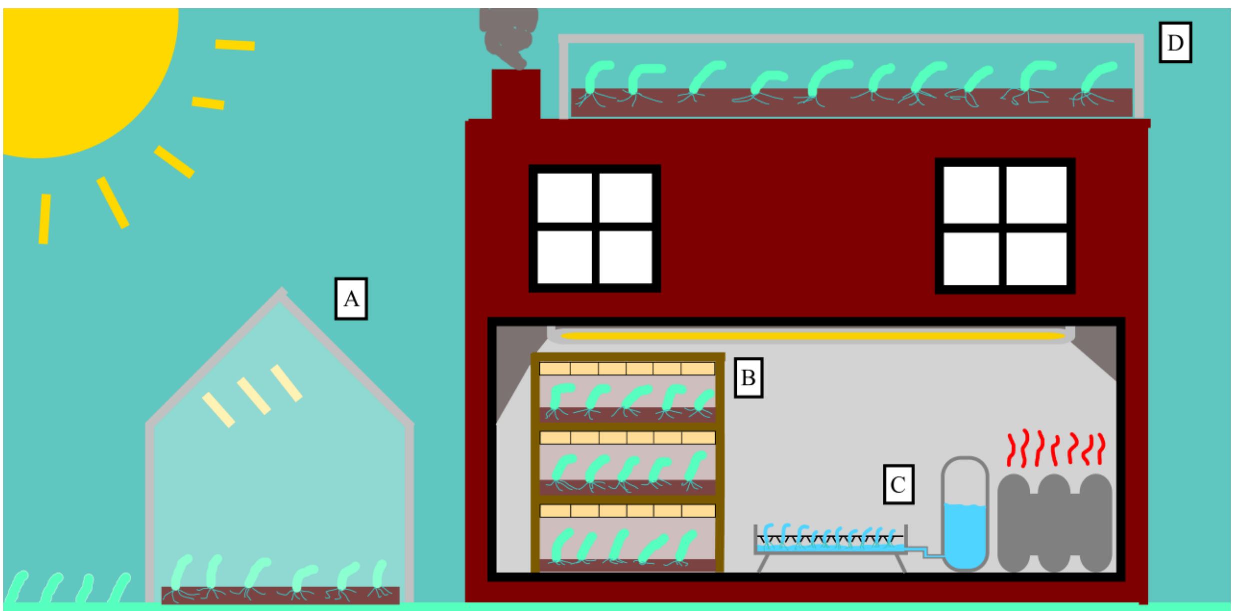
Literature Review

Background & proposed benefits of CEA

The idea of controlled-environment agriculture has existed for more than a century, with the first known mentions of "vertical farming" and "hydroponics" being in the early 1900s (Goodman et al, 2019). Generally, CEA is a broad term which encompasses a wide range of agricultural technologies, from simple glass greenhouses exposed to sunlight to automated soilless farms powered by LED fixtures. This paper will primarily focus on CEA operations with the intent of large-scale food distribution and consumption.

Greenhouses and tunnels are the most distilled and simplified form of CEA. Both are made of transparent building materials, with greenhouses being made of glass and tunnels being made of plastic, to allow solar radiation to reach the plants. They exist in many applications, from large plastic tunnels in a rural countryside to an enclosed glass roof of an urban apartment building. The enclosed nature of a greenhouse or tunnel means that much of the heat introduced by the sun remains inside the structure, keeping crops warm even if external temperatures decrease. However, this natural heat capture often isn't enough to maintain ideal growing conditions in some areas, so many greenhouses and tunnels employ additional heating or lighting technologies (Graamans et al, 2018).

A majority of alternative CEA methods are highly technological in nature. One such example is vertical farming, a practice in which the natural sunlight demand of crops is replaced with LED light, allowing crops to be grown in arrays stacked on top of each other in a closed space. Vertical farms also often utilize hydroponics, a system in which crops are grown in the absence of soil, with their roots being directly supplied with a nutrient-rich solution instead (Barbosa et al, 2015). Unlike greenhouses, vertical farms, and hydroponic systems all require energy expenditure to supply light, heat, and sometimes even water to the crops (Figure 1).



Characteristic		Method of delivery to plants			
CEA Type	Frequency	Temperature	Water	Light	Nutrients
A: Greenhouse	41%	Natural or artificial	Artificial	Natural	Artificial
B: Vertical Farm	18%	Artificial	Artificial	Artificial	Artificial
C: Hydroponics	5%	Artificial	Artificial	Artificial	Natural or artficial
D: Rooftop Farm	3%	Natural or artificial	Artificial	Natural	Artificial

Figure 1: A simplified drawing of CEA farm types of interest along with information about their frequencies out of a survey of 315 farms in the United States, as well as how conditions for plant growth are maintained (Dimitri et al, 2016; Engler et al, 2021).

While a fledgling industry, CEA is already established in several areas of the world (Figure 1). In Europe, the largest concentration of CEA farms exists in Almería, a rural province in southern Spain in which greenhouses take up approximately 30,000 hectares of land. In Almería, traditional field farming was prevalent until around 1980, but by 2000, intensive greenhouse agriculture had replaced fields almost entirely (Callejón-Ferre et al, 2009; Mendoza-Fernández et al, 2021). Large CEA complexes like these can be used to directly compare outputs between large-scale CEA and traditional farms. However, CEA experiments have been most prevalent in urban environments due to the purported land and water efficiency of CEA. Additionally, by distributing food in high-density population centers, less need for high-emissions transportation arises. Local communities may also become involved in urban agricultural production, bringing cities closer to achieving agricultural self-sufficiency. New York City is an area frequently cited in case studies of CEA in urban areas, being the densest metropolis in the United States with over one hundred farms currently in operation (Dimitri et al, 2016; Goodman et al, 2019).

Ultimately, those championing CEA claim that it posits a solution to the unsustainability of modern industrialized agriculture. Indoor farming shields crops from external complications like disease, tumultuous weather, or pests, which have all served as historical impediments to the success of agriculture. Some also claim that CEA may provide more healthier food in urban areas, where access to fruits and vegetables may be limited (Benke et al, 2017). As such, this review will focus primarily on the external impacts of food production via CEA, such as energy consumption, ecological impact, and socioeconomic nuances, when compared to traditional agricultural structures.

Impact & Implications

As a global phenomenon, studies of CEA have taken place throughout the world under a diverse range of technological and economic circumstances. By aggregating data from several studies, this section aims to explore key facets of CEA production, including environmental, economic, and social implications. From there, recommendations can be made about how CEA's real-world performance compares to its proposed benefits.

Environmental and ecological footprint

Energy intensiveness

One metric by which the environmental viability of CEA has been measured is the energy required to sustain environmental conditions indoors. Industrial field farming, although intensive on the land's resources, doesn't use artificial lighting, heating, or cooling that may result in emissions and extraction outside of the agricultural space. When it comes to greenhouses, local climate plays a significant role in energy expenditure. For example, studied greenhouses in Sweden, a country with a cold/temperate climate, required heating to constitute a majority of the non-renewable energy demand of the entire greenhouse. Alternatively, in the United Arab Emirates and Algeria, countries with a hot/desert climate, the majority of non-renewable energy required was for dehumidification and cooling (Graamans et al, 2018; Mostefaoui et al, 2019). Ultimately, heating/cooling constitutes up to 50% of the total energy demand in warm climates such as Algeria and the UAE, and up to 85% of the demand in northern latitudes such as Sweden and the Netherlands. Seasonal differences play a large part in energy expenditure as well, since local conditions can change drastically throughout the year. In Algeria, during the coldest and warmest months such as January, July, August, and December, around 2 kilowatts of energy was required to sufficiently heat/cool crops. However, in April and October, no energy was required for climate control as ventilated air from the environment was already at a suitable temperature (Mostefaoui et al, 2019. For vertical farms, however, differences in energy expenditure across were almost nonexistent. Being in a controlled agricultural space, plant factories experience less external influence from the local climate, so they generally require the same amount of energy to maintain conditions universally. This was reflected in relatively uniform total energy demands measured in plant factories across Sweden, the Netherlands, and the UAE (Graamans et al, 2018; Figure 2).

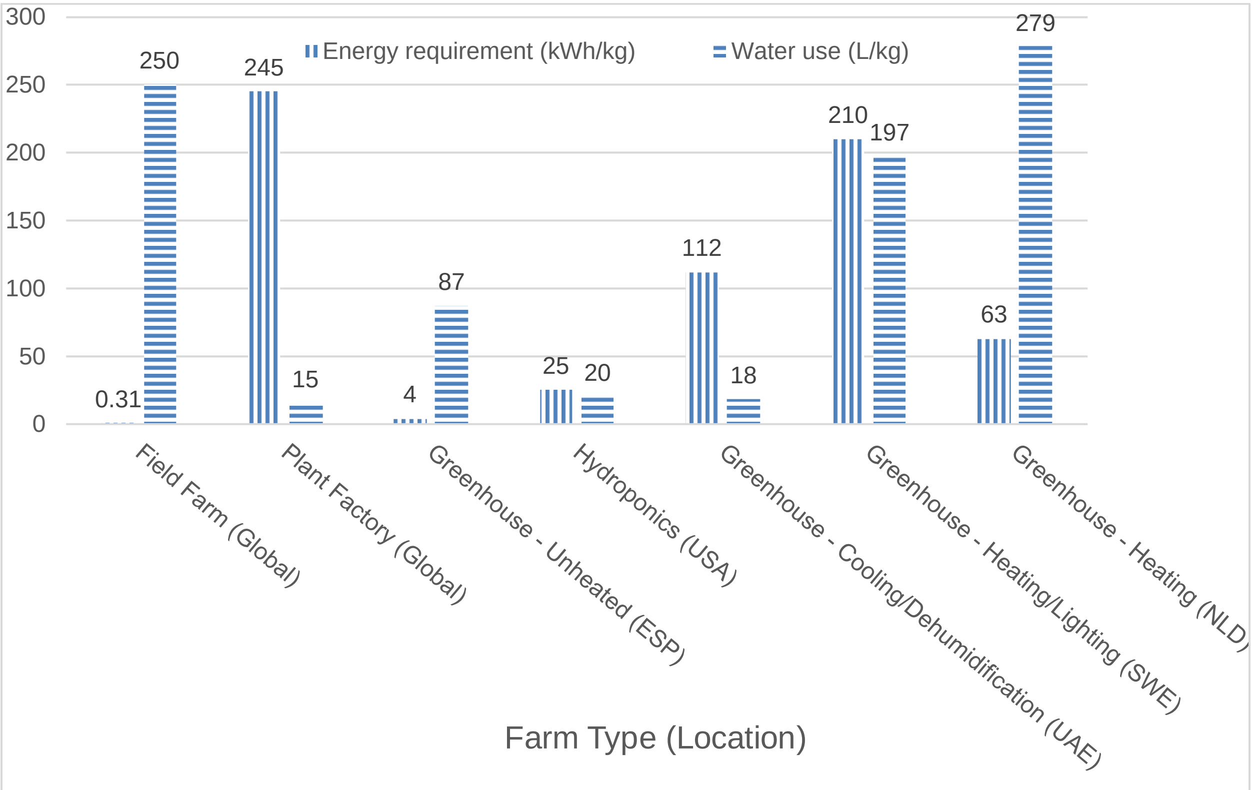


Figure 2: Aggregated data from several studies comparing total electrical energy consumption and water use per kilogram of lettuce/tomatoes produced, across different types of farming across various levels of technological intensiveness (Graamans et al, 2018 [SWE, NLD, UAE]; Barbosa et al, 2015 [USA; Global]; Mendoza-Fernández et al, 2021 [ESP]).

The energy requirements of a farm are also dependent on the level of technology in the operation. One study found that in vertical farms, the electricity demand by LEDs required to artificially illuminate or heat crops constituted over 75% of the farm's total energy demand, across all climates. In contrast, greenhouses required most energy be spent on artificial cooling, heating, and dehumidification (Graamans et al, 2018). Greenhouses also tended to use more renewable energy, with photovoltaic solar panels requiring a large (but clean) energy input due to PV panels being relatively inefficient. When it came to non-renewable energy expenditure, vertical farms expectedly had larger non-renewable energy expenditures than less intensive greenhouses between the two CEA structure types (Engler et al, 2021). Overall, across multiple studies, plant factories such as vertical farms consumed the most energy, followed by intensive greenhouses (with the energy intensiveness increasing with a greater climate control requirement), followed by hydroponics in a hospitable climate, with the least energy intensive form of CEA being greenhouses in a hospitable climate (Figure 2).

The source of energy that CEA farms use to supplement this energy demand is of paramount importance when considering energy intensiveness. Agricultural literature makes a point to distinguish between renewable and non-renewable energy sources for CEA due to the multifaceted differences in environmental impact between renewable and non-renewable energy. While electricity can be a renewable resource, many electrical grids still operate on fossil fuels and necessitate CO_2 emissions. Ultimately, studies suggest that a clean electrical grid is necessary for energy-intensive CEA operations to create less emissions than field-farming to begin with (Theurl et al, 2014). Hence, most studies concluded in favor of using PV panels as a source of energy for CEA despite their relative inefficiency. Greenhouses tend to have greater access to renewable solar energy via photovoltaic panels due to having a larger surface area with access to solar radiation (Mostefaoui et al, 2019). Ultimately though, energy sources are generally dependent on the local electrical grid of each farm as opposed to varying by level of technology.

Emissions and global warming potential

The agricultural sector is responsible for approximately one-third of total greenhouse gas emissions from sources such as deforestation, fertilizers, and crop burning. Emissions are also strongly correlated with energy consumption due to the amount of energy sources that remain dependent on fossil fuels (Engler et al, 2021). However, this figure doesn’t include external sources of emissions, such as transportation, refrigeration, and packaging manufacturing. One study conducted across Europe examined the “global warming potential” of tomatoes (defined as grams of CO_2 equivalent per kilogram of tomatoes produced) from their growth to their sale in Vienna, Austria (Theurl et al, 2014). The study was holistic, examining the growth, packaging, and transportation of the tomatoes separately. Four European tomato producers were studied: two local farms in Vienna (one glass greenhouse and one tunnel farm) where the winter climate is inhospitable for growing tomatoes traditionally, a CEA tunnel in Almería, and a traditional field farm in Italy with a year-round farming climate.

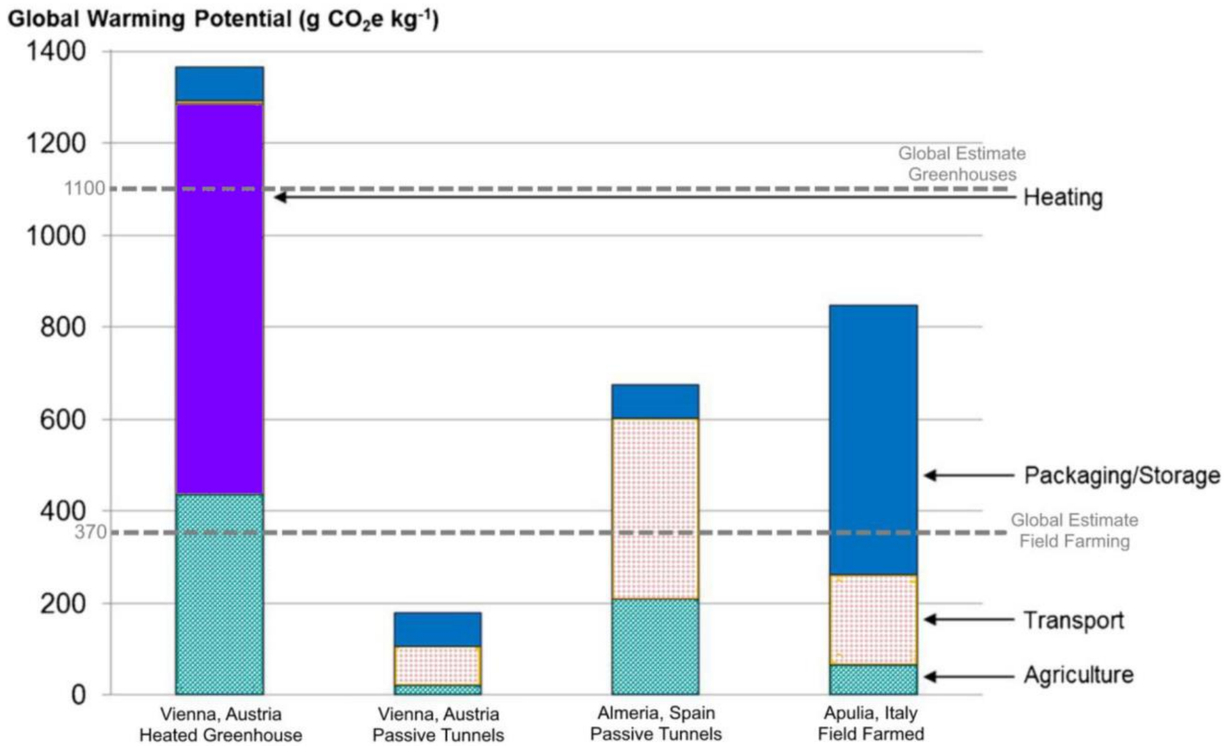


Figure 3: Global warming potential of tomatoes grown locally in Austria compared with imported tomatoes from Spain & Italy, categorized by farming method alongside the global estimate for each farming method (modified from Theurl et al, 2014; Engler et al, 2021).

The study found that the locally grown tunnel-farmed tomatoes had the lowest global warming potential out of all four farms (180 g CO_2e per kg tomatoes in total). In Vienna, these tunnels didn't require heating since the plastic insulated them sufficiently. The heating requirement of the glass greenhouse in Vienna alone (848 g CO_2e per kg tomatoes) created more global warming potential than the entire global warming potential of the three other farming systems from farming to the supermarket (Theurl et al, 2014). In this instance, the transportation emissions saved by growing locally didn't offset the emissions created by maintaining conditions via heating. Between the two imports, the CEA in Almería created less global warming potential than the traditional field farm in Italy. Both farms necessitated significantly more transportation emissions than the local options (392 g CO_2e per kg tomatoes from Almería and 196 g CO_2e per kg tomatoes from Italy). However, the crops from Italy required intensive packaging, creating another 447 g CO_2e per kg tomatoes. These farms didn't require heating, so they both still had less global warming potential than the local greenhouse. Therefore, in this instance, the agricultural method that produced the least emissions was the method in which food was grown both locally and without intensive climate control (Theurl et al, 2014).

One method by which CEA and urban agriculture can directly reduce carbon emissions is by acting as a carbon sink and fertilization. One study found that rooftop farms in dense urban areas could store up to 0.76 kilograms of carbon per square meter, reducing the heat island effect in cities (Orsini et al, 2014). Additionally, farms with a heating requirement, such as the local greenhouse in Vienna, utilized CO_2 fertilization, wherein emissions from heating were partially recycled as a nutrient to fertilize crops. While this method does reduce overall emissions, it encourages the emission of CO_2 by heating the crops in the first place (Graamans et al, 2018).

Land and water use

CEA's ability to function irrespective of outside conditions can impact the resources it may require. In urban areas, CEA can exist in small, repurposed spaces such as basements or terraces. One study estimated that urban greenhouses and rooftop gardens could offset 77% of a city's urban vegetable demand, which would significantly offset the amount of rural deforestation and degradation necessary to feed the population (Orsini et al, 2014). Vertical farms, by stacking plants in opposed to having only one layer across, are unequivocally more space efficient than traditional farms. For soil-based CEA, plants still need to be spaced apart to make space for roots to grow. However, for hydroponics, land use was demonstrably lower than conventional farming since plant roots can be funneled directly downwards (Figure 1). While conventional farms yielded 3.9 ± 0.21 kilograms per square meter per year of lettuce, a hydroponic system could yield as much as 41 ± 6.1 kilograms per square meter per year of lettuce (Barbosa et al, 2015). The same study found that hydroponics also saved water, as hydroponically grown lettuce required 20 ± 3.8 liters of water per kg of lettuce per year, whereas conventionally grown lettuce required 250 ± 25 liters of water per kg of lettuce per year (Figure 2). In soil-based farming, water is dispersed liberally throughout soil, leading to some inefficiency. However, water is more likely to be pumped or tightly irrigated in CEA farms (Mostefaoui et al, 2019).

Water usage also relates to the evapotranspiration of crops. In field farms, being exposed to ample heat and sunlight causes significant water loss due to evaporation. As such, systems that are closed from the external environment proved more water efficient than those which are semi-open or open. With soilless CEA, water can be recycled, leaving evapotranspiration as the main source of continual water consumption (Graber et al, 2009). This means that vertical and hydroponic farms are the most water efficient, and traditional farms are the least efficient, with greenhouses falling in the middle (Graamans et al, 2018).

Biogeochemical cycling

One of the National Academy of Engineering's Grand Challenges for Engineering is to "manage the nitrogen cycle" (NAE, 2019). While biogeochemical cycles are critical processes that facilitate the growth of crops, their mismanagement can have adverse effects on the environment. Studies have found little difference in the amount of nitrogen & phosphorus fertilizer necessary to cultivate crops between field farms and soil-based greenhouses (Theurl et al, 2014). However, farmers' lack of control over excess nutrients can result in stormwater runoff, which picks up nitrogen or phosphorus from open farmland. If these nutrients infiltrate water supplies, they can lead to excess microbial growth (called eutrophication), leading to aquatic life dying from a lack of available oxygen in the water. In a greenhouse, soil is impervious to rain, mitigating eutrophication from stormwater runoff. Nitrogen and phosphorus-enhanced soils can also be recycled in soil-based greenhouses & vertical farms, and the nutrient-rich solutions used in hydroponics can also be recycled (Graber et al, 2009).

Nitrogen and sulfur oxides from industrial and vehicle emissions is a contributor to acid rain, which in turn can damage ecosystems as well as unprotected fields and crops. Local CEA in city centers would reduce the nitrogen and sulfur oxide emissions commonly associated with transportation, mitigating acid rain. Carbon fertilization is also a form of biogeochemical recycling, since it reuses heating emissions to fertilize crops. Some more advanced systems take nutrient cycling further. One such example is aquaponics, which uses the nutrient-rich waste produced by fish as food for crops. One study found that hydroponics can recycle up to 34% of the nitrogen required for tomato growth, which rises to 69% when incorporating aquaponics (Graber et al, 2009). This study also suggested that these systems have the potential to work in tandem with the denitrification of urban and rural municipal wastewater, recycling nutrients from human waste.

Economic factors

Market space and demand

CEA currently exists in a different market space to traditional agriculture. The vast majority of crops on supermarket shelves are still grown traditionally. However, as public sentiment moves further in favor of healthy eating and environmentalism, there is an emerging demographic interested in purchasing local crops grown using sustainable new technologies. 40% of urban CEA farms are not-for-profit, with many existing as a part of educational school programs and community gardens. These not-for-profit farms tended to have a less sustainable business model, but overall have the potential to increase consumer demand for healthy and environmentally sustainable agriculture through education and community involvement (Dimitri et al, 2016). The profitability of CEA for a business is highly crop-dependent, due to various crops having vastly divergent requirements for maintaining environmental conditions. The most profitable crops grown in NYC's CEA farms when accounting to the costs of production tended to be leafy greens and herbs, which are of "only moderate nutritional value". As such, for-profit CEA operations tend to focus on catering to wealthy consumers who are willing to purchase such crops from CEA producers due to a perceived environmental benefit (Goodman et al, 2019).

Capital investment and costs of production

As with many technologically intensive businesses, vertical and hydroponic farms require a large initial capital investment in technology, labor, and real estate. In concentrated urban areas, real estate comes at a premium and has served as a barrier to the profitability of entrepreneurial CEA businesses. In rural areas such as Almería, where energy and real estate were less expensive, energy accounted for only 1.50% of total costs while labor costs comprised 45% (Mendoza-Fernández et al, 2021). Various types of CEA also saw various levels of profitability. By account of the 2012 National Survey of Urban Farms, hydroponic farms average $112,071 a year in sales, with the next most profitable option, tunnel farming, averaging only $73,551. Greenhouses averaged $62,387 of sales per year in urban areas. Non-profit farms, which are more likely to be less technologically advanced, were reported to be more likely to require external donations and subsidies to sustain operations, but were less likely to limit production to crops of lower nutritional value (Dimitri et al, 2016).

Despite the high barrier to entry of starting a high-tech CEA business, energy and maintenance costs can balance that out to some degree. Low-tech greenhouses have been studied to excel at reduction of purchased energy due to their access to free solar energy, which makes them anywhere from 14-200% more cost-efficient than artificial lighting and heating in vertical farms (Graamans et al, 2018). In Algeria, the initial investment in a photovoltaic energy capture system was almost twice that of an equivalent diesel pump for water irrigation, but when levelized for the lifetime of the system, the cost of energy was $0.068 per kWh whereas the cost of energy for the diesel pump was $0.230 per kWh (Mostefaoui et al, 2019). Studies agreed that the local costs of water, land, and energy, efficiency directly correlates with the profitability of CEA operations.

Labor

Labor is a necessary cost in both traditional farming and CEA alike to operate equipment and collect harvests. Much of the same demand that fuels the limited market success of CEA would also advocate toward paying workers a livable wage as opposed to minimum wage. Despite this, workers in CEA farms in NYC were found to be paid anywhere from minimum wage to slightly above a living wage, and across the United States there is only a 28% chance that the primary farmer of an urban CEA farm earns their primary living through the farm. In the United States, there was minimal difference in whether laborers made a living wage between non-profit and for-profit CEA, but both occurred less frequently than in traditional farms. However, one disparity between non-profits and for-profits is that non-profits can use unpaid volunteer labor to sustain operations, whereas commercial farms are prohibited from using unpaid labor as per United States law (Dimitri et al, 2016).

Various types of CEA also exhibited different properties in terms of the labor market. Between technologically intensive farms and rural greenhouses, different employment niches/"skill levels" are required to maintain operations, with vertical and hydroponic farms requiring more technical experience. One study suggested that this diverse range of employment gives the space potential for job creation (Goodman et al, 2019). In Almería, low-tech greenhouses were found to be conducive to high levels of immigrant labor. Working conditions in these greenhouses were substandard, and laborers in Almería were deemed to be exposed to health risks at work due to long working hours and an excessively hot thermal environment (Callejón-Ferre et al, 2009).

Social Consequences

Public perception of CEA

As with any new technology, adoption is slow and some resistance is inevitable. One case study in New York City found that residents varied significantly in their perceptions of CEA. A large portion of those surveyed reported to be either unaware, lacking knowledge, or ambivalent about CEA. Generally, people reported feeling resistant to "unnatural" methods of growing crops, such as hydroponics, aquaponics or vertical farming. Primarily, respondents were put off by the idea of growing crops without soil. Greenhouses, a form of CEA which is soil-based, less technologically intensive and has existed for centuries, did not receive as much skepticism. As a result, high-tech CEA was overall perceived to be less desirable than agriculture grown using traditional, more common methods (Broad et al, 2021).

Aspects of agriculture consumption that consumers reported to care most about were that the food was local and grown without pesticides, both of which are more likely to be true in CEA farms but aren't inextricably linked with the technology. Respondents also responded negatively to the implicit association between CEA and genetically modified agriculture. While genetically modified seeds may commonly be used in CEA agriculture, they are not inherent to the technology and many operations don't use genetically modified seeds at all. Consumers also largely desired transparency over where food was grown, the methods by which it was grown, and how long it had been on shelves. Reports also noted that these perceptions are likely change in the future, as the technology is used more frequently and becomes tried and tested (Broad et al, 2021).

Community impact

Many studies indicated that a change in the way food is produced and distributed could change how communities interact with food. Currently, the supermarket model provides little connection between the producers and consumers of agriculture. However, local CEA farms were found to be more likely on average to adopt social goals such as providing nutrition education, volunteer opportunities, and community building (Dimitri et al, 2016). Survey respondents said they would have more trust in CEA as a technology if this relationship between producers and the community was fostered (Broad et al, 2021).

In Almería, previously a relatively poor rural area, the infusion of funding due to greenhouse projects led to economic development in the region. Urban areas could evolve similarly through gaining more control over supply chains by growing food locally (Mendoza-Fernández et al, 2021). Some researchers mention that local CEA could potentially reduce the amount of food deserts, which are defined as an urban area where residents have no convenient or affordable access to fruits and vegetables. Research into CEA is also seen as an opportunity for nutrition education in places like the United States (Goodman et al, 2019).

Policy and government involvement

Since CEA is a budding technology, there are ways in which CEA is treated differently than traditional agriculture in legislation and regulation. Agricultural policy and law in the United States rarely mentions CEA specifically, making it difficult to determine how certain regulations apply. Most of the EPA's agricultural regulations cover pesticides, waste management, and rural land use, which are not applicable to most forms of CEA. The EPA also has emissions regulations for farms, but since energy-intensive CEA outsources emissions from electricity and keeps local emissions relatively small, it's currently unclear how those regulations apply. Greenhouses, however, are specifically regulated in terms of building and zoning codes, and the US Department of Agriculture has a bespoke greenhouse certification program (EPA, 2021).

Few governments or policymakers have acknowledged CEA as a legitimate form of agriculture. This is interrelated with a general lack of public knowledge about the technology. One notable exception is in NYC, where mayor Eric Adams has explicitly allocated over 2 million dollars towards CEA initiatives including hydroponic farms in public high schools. Many non-profit organizations in the New York area receive subsidies from the government as well. It isn't certain whether this investment has made a meaningful impact on surrounding communities in terms of reducing food insecurity or improving nutrition education (Goodman et al, 2019).

Recommendations

In terms of environmental impact and sustainability, CEA shows promise as being more sustainable than traditional field agriculture. Perhaps the most significant and the most consistent benefit of CEA over field farming comes in the form of reduced extraction from the Earth. From greenhouses to vertical farms, CEA consistently proves to require less land use and less fresh water, although savings are larger with high-tech CEA as opposed to greenhouses. In a world where agriculture plays a significant role in the depletion of global supplies of both freshwater and arable land, utilizing CEA in environments where these resources are scarce could be extremely valuable.

The largest environmental drawback of CEA is the energy demand necessary to sustain specific environmental conditions throughout the year. Consistently across studies of high-tech CEA, the largest contributor to energy demand (as well as the cost of operations) were temperature controls, especially out-of-season during the warmest/coldest months of the year. It simply isn't environmentally or economically viable to expend inordinate amounts of heat, cooling, or dehumidification to sustain seasonal crops when the climate doesn't support it. While somewhat antithetical to the promise of CEA, this paper recommends that, if necessary, only minimal amounts of climate control be used to grow crops indoors.

High-tech CEA farms, and greenhouses to a lesser extent, are reliant on electricity, and thus a source of renewable energy or a clean local power grid is also highly recommended for CEA to be environmentally viable. Greenhouses strike a happy medium in terms of energy consumption. Greenhouses naturally trap heat, insulating crops to a certain extent without the need for energy consumption. Even still, greenhouses are more likely to fit photovoltaic solar panels on the greenhouse roof or in adjacent fields, and PV panels are proven to be cheaper in the long run than relying on non-renewable energy. Since greenhouses aren't completely closed systems, they also don't require the climate control that makes plant factories so intensive out of season.

CEA's potential for emissions reductions is highly situational, depending on the transportation, energy consumption, and level of climate control necessary. While enclosed CEA allows for more control over emissions and waste management, it doesn't always reduce overall emissions. Reusing heating emissions using techniques such as CO_2 fertilization provides a temporary and overall insignificant level of mitigation against emissions. Examples show that incentivizing the emission of CO_2 in the first place can be more deleterious than current agricultural methods even when considering this mitigation. A similar variability exists when it comes to the cycling of nitrogen and phosphorus-based fertilizers, with no major inherent difference between soil-based CEA and field farming. However, when it comes to soilless agriculture, there are some joint applications of nutrient-recycling methods such as aquaculture and wastewater treatment denitrification that exhibit potential to recycle nitrogen effectively, which should be studied further to determine viability.

All of this means that CEA can be better or worse for the environment than field agriculture depending mostly on local factors. This paper recommends that any agricultural development take into consideration land scarcity, climate, budget, reliance of electricity on non-renewable energy, and water scarcity of the locality, choosing the form of agriculture that is least reliant on the most deleterious metric for that location. For example, while not the most economical, a hydroponic farm in a region facing drought or lack of fertile soil is a good option to reduce strain on the water supply. Alternatively, in a region where the electrical grid is still reliant on burning fossil fuels and costs need to be low, a traditional field farm may remain a better option than any type of CEA. Greenhouses without a purchased heating requirement are almost always a good environmental option and function as a suitable default option if these parameters are unknown.

Economically, CEA will require immense investment and targeted attention to become viable on a widespread scale. Building the infrastructure that advanced CEA requires, including even a simple greenhouse, is an undertaking of a large capital investment, not to mention real estate or labor costs. In rural places, greenhouses can be cost-effective over time if solar energy is used. However, especially in urban areas, the investment required to create space-efficient agriculture in expensive real estate can be astronomical. This translates into CEA-grown food being more expensive for consumers, so most for-profit CEA businesses tend have wealthy owners which target wealthier consumers. Despite the profitability of high-tech CEA, this result stands diametrically opposed to the purported increase of food availability to urban residents that CEA could provide. However, advancements in technology that may reduce the cost of high-tech CEA is possible, and this paper encourages the continued pursuit of innovation.

Overall, CEA does have the potential impact urban social dynamics in a positive way. CEA is touted as a sustainable technology by both businesses and non-profits alike. While this may not always be true compared to traditional farming, CEA's potential for nutrition education and local connections between producers and consumers can be positive. Often, demographics who are concerned about their environmental impact are more likely to be receptive to CEA. Nutrition education could also lead to a change in habits away from year-round demand for certain crops, reducing the amount of environmental extraction needed to support out-of-season fruit and vegetable demand. This local approach could also reduce food insecurity by subverting the grocery store model of distribution, instead allowing for local farmers to sell directly to consumers via a farmers market or similar mechanism, reducing costs in the process. Tying in with the common themes of CEA, such improvements are not inherent to CEA. Farmers markets are already an option for many local field farmers, and a similar model of direct exchange should be pursued across all types of agriculture. However, by putting more food in population centers, the technology can facilitate lower costs and accessibility to healthy food.

It is paramount that urban areas become more agriculturally self-sufficient. Rooftop farms alone have been estimated to be able to cover a majority of urban vegetable demand, reducing the need for deforestation and land exploitation in rural areas, as well as transportation emissions which constitutes significant portions of agricultural emissions. Overall, CEA can help achieve this by expanding the amount of urban land that could feasibly be used for agriculture. However, CEA isn’t necessary to fulfill urban agricultural demands, and can often even stand in the way of doing so in a sustainable and equitable manner. Due to economic feasibility and environmental impact, low-tech rooftop greenhouses and even traditional community gardens will usually be preferable over high-tech options. Parking lots or abandoned spaces could be converted to natural gardens or greenhouses. In suburbs, water-intensive lawns could be converted into small gardens. High-tech CEA should rarely be necessary in rural areas, since local populations can already be fed by current agricultural outputs from greenhouses or field farms, even with inhospitable climates throughout some of the year. Urban self-sufficiency shouldn’t interfere with the economic viability of rural agriculture due to the disparities in crops grown between the two types of farms.

Conclusion

It is clear that current methods of industrialized agriculture aren’t sustainable. As arable land diminishes and growing seasons become more unpredictable, it appears that feeding the growing population through traditional means will become increasingly challenging. This makes the advent of CEA all the more exciting, since proponents claim it can solve many of these challenges. However, literature suggests that the environmental, economic, and social benefits of CEA are highly situationally dependent with some clear upsides and downsides. As such, this paper recommends the further pursuit of CEA as an alternative to traditional field-farming, while acknowledging that its current viability is extremely circumstantial.

In its current form, CEA does succeed at providing a potential solution to the excessive use of land, water, and pesticides that plagues traditional industrial agriculture. However, it is a long way from being the practical solution to modern agriculture’s problems that its proponents claim it to be. In practice, CEA is energy intensive, polluting, and prohibitively expensive for both producers and consumers. Out-of-season growth, a commonly touted benefit of CEA, is economically and environmentally infeasible due to energy demands. Current studies are also unable to indicate the social impacts that CEA may have, although most agree that the potential exists for CEA to lead to more equitable forms of food distribution. Imported agriculture, distribution via grocery stores, and food waste have all contributed to food insecurity, and it's unclear how CEA would remedy these problems. More research is needed, including real-world trials, into how CEA impacts producers and communities before it should be implemented at a large scale.

As certain aspects of consumption and infrastructure improve, such as a shift to renewable energy, devoting less space to cars in urban environments, and stricter regulations on nationwide emissions, CEA will become more sustainable alongside them. Despite this, reducing energy expenditure and extraction of the Earth's resources to begin with will always better protect the Earth than continuing to heavily use the planet's finite resources in the meantime. Growing food locally, inexpensively, with low energy consumption, and in a community-driven manner is already possible through rooftop farming and community gardens. While high-tech CEA develops and improves, urban governments should invest in local agriculture projects and clean energy systems that will lay the foundation for CEA to potentially rise later on in a widely accepted and more sustainable manner.

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